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AD-A165 489

AFWAL-TR-85-2052

CONCEPTUAL DEVELOPMENT OF STRAIN-GAGE SIGNAL INTERPRETATION SYSTEM FOR JET ENGINE APPLICATIONS

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October 1985

Final Report for Period February 1983 - March 1985

Approved for public release; distribution unlimited.

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SECURITY CLASSIFICATION OF THIS PAGE

AD-A165489

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b RESTRICTIVE MARKINGS

2a SECURITY CLASSIFICATION AUTHORITY

2b DECLASSIFICATION / DOWNGRADING SCHEDULE: N/A

3 DISTRIBUTION / AVAILABILITY OF REPORT: Approved for Public Release; Distribution Unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S): R85-956394-R1

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFWAL-TR-85-2052

6a NAME OF PERFORMING ORGANIZATION: United Technologies Research Ctr

6b OFFICE SYMBOL (If applicable): UTRC

7a. NAME OF MONITORING ORGANIZATION: AFWAL/POTX

6c ADDRESS (City, State, and ZIP Code): Silver Lane, East Hartford, CT 06108

7b ADDRESS (City, State, and ZIP Code): Wright Patterson Air Force Base, Ohio 45433

8a NAME OF FUNDING / SPONSORING ORGANIZATION: U.S. Air Force

8b OFFICE SYMBOL (If applicable): USAF

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F33615-82-C-2263

8c ADDRESS (City, State, and ZIP Code): Wright Patterson Air Force Base, Ohio 45433

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
61102F	2307	S1	41

11 TITLE (Include Security Classification): Conceptual Development of Strain-Gage Signal Interpretation System for Jet Engine Applications

12 PERSONAL AUTHOR(S): Ray M. Chi, Deborah C. Haas, William C. McClurg, Philip E. Zwicke

13a TYPE OF REPORT: Final Report

13b TIME COVERED: FROM 2/83 TO 3/85

14 DATE OF REPORT (Year, Month, Day): October 1985

15 PAGE COUNT: 109

16 SUPPLEMENTARY NOTATION

17 COSATI CODES

FIELD	GROUP	SUB-GROUP
21	01	

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Strain-Gage Signal Interpretation; Aeromechanical Responses

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

In this strain signal interpretation program, a systematic study was made in order to define the hardware/software configurations of an expert system capable of monitoring and interpreting strain-gage signals from jet engine compressor stages and immediately taking necessary evasive actions to ensure rig safety. First

A comprehensive strain-gage data bank was ~~first~~ generated that contains all major categories of aeromechanical phenomena and noise signals from fan and compressor stages of various engines. The strain-gage data were analyzed in both the time domain as well as the frequency domain to identify significant signal features for various types of aeomechanic phenomena and noise. These individual signal features were combined with spatial (interblade and interstage), temporal and other syntactic features to form a complete feature set for each aeromechanical phenomenon or noise type.

The feature sets of all strain gages were then used in a three level classifier sytem

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL: R. D. DeRose

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22c OFFICE SYMBOL: AFWAL/POTX

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

to determine the probability values of each possible aeromechanical phenomenon and noise type. The first classification level ~~of classification~~ uses only the individual strain gage feature to determine the category probability for each phenomena and noise type. The second level of classification ~~utilizes~~ uses the spatial (interblade and interstage) features to refine the category pseudo-probability values and yield the event probability values. The third level of classification combines the temporal features with the event probability values to yield the final probabilities based on which decisions are made on the type of actions to be taken to ensure rig safety.

The baseline software/hardware system specifications have been defined to acquire strain-gage data, calculate global features, then use these features to determine the predominant aeromechanical phenomena. Up to 100 strain-gage channels are to be incorporated into the system on a modular basis. A one-per-rev signal provides engine speed information. Each channel carries an analog signal to a data acquisition module. The signal is digitized and 4K of data corresponding to 0.8 sec is buffered. An array processor calculates the stress, histogram, and FFT global features for 15 to 20 channels. The actual number of channels depends on the particular array processor selected. A supervisory minicomputer uses the global features from all channels to classify the aeromechanical phenomena and to take evasive action if necessary. The minicomputer operates in parallel with the array processor. The overall system is expected to produce real-time displays within a one-to-two-second update rate during on-line operation.

PREFACE

The work reported herein was conducted by the United Technologies Research Center (UTRC) for the Aeronautical Systems Division, Air Force System Command (AFSC), Wright Pattereson Air Force Base under contract F33615-82-C-2263, "An Exploratory Study of Strain Gage Signal Interpretation." The technical monitor for the Air Force was Mr. Robert D. DeRose. The UTRC program manager was Ray M. Chi.

Special recognition is due to those engineers who contributed to the exploratory study of interpreting strain gage signals and the subsequent conceptual development of an on-line strain gage interpretation system. Arthur R. Gurette of Pratt & Whitney was responsible for organizing the extensive strain gage data bank used in the data analysis phase of the contract. Hans Stargardter, William D. Keiran and Arthur R. Guerette strode through the thicket of data tapes to identify representative signals for various aeromechanic phenomena and Robert A. Yeich and colleagues expertly digited the signals before delivery to UTRC. The wealth of aeromechanics knowledge of Hans Stargardter, William D. Keiran and Arthur R. Guerette formed the firm basis for the selection of features in the classifier development.

At UTRC, Charles E. Walker and Cynthia G. Egolf loaded P&W digital data into the Univac computer for interactive data processing. Philip E. Zwicke initiated the multilevel classification scheme based on a degradation logic and developed the software logics for the signal classification. With the help of Cynthia Egolf, Ray M. Chi performed probability calculations using selected strain gage data to demonstrate the feasibility and usage of the degradation logic. Martha Hart was involved in the last stage of the long data processing task. The software and hardware system specifications were defined by Deborah C. Haas and William C. McClurg.

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

TABLES

1.0 INTRODUCTION

The dynamic response of the compressor blades during a typical compressor test is constantly monitored by observing dynamic strain gage responses on a real-time basis. The number of strain gages is generally very large and several aeromechanic test engineers may be required to monitor strain gage oscilloscopes continuously for a long period of time. Eye fatigue or momentary loss of concentration could result in overlooking excessively high vibratory stresses, hence, causing serious damage to the blades and possibly the entire test vehicle. It is therefore desirable to have a computerized vibratory stress monitor to ensure the structural integrity of the test compressor. This computerized vibratory stress monitor or on-line real-time strain-gage signal interpretation system becomes more desirable, if the compressor performance testing facility is also driven by a computer programmed to search for optimum vane and bleed settings in multistage flow machines. The total concept would contribute to potentially large cost reduction in compressor development programs.

The state-of-the-art strain-gage monitoring systems (e.g. Refs. 1, 2, 3) either depend entirely on human judgement in identifying aeromechanical conditions of the test vehicle, or assume only limited capability in automatic detection of flutter and resonant vibrations. Recently, a comprehensive study on the subject of engine strain-gage signal interpretation was undertaken in order to establish the foundataion for building a computer-aided strain-gage expert system applicable to multistage compressor testing (Ref. 4).

The objective of the program was to define software and hardware specifications for a computerized on-line real-time system capable of classifying up to 100 strain-gage signals and initiating necessary evasive actions to ensure test vehicle safety.

The major problems in developing such a powerful real-time system are the following:

(1) The system has to be reliable (for all test compressors under a wide range of operating conditions) in detecting all potentially dangerous dynamic stresses being monitored without missing any high-stress blade responses.

(2) The system has to be fast in response regardless of the generally large quantity of dynamic strain gage signals recorded simultaneously.

To deal with the first problem, a collection of strain-gage signals recorded previously in various compressor performance tests was analyzed in order to identify and confirm important features associated with various types of strain-gage responses due to different aeromechanical phenomena. These featues were used in the development of vibration classifiers. The second problem was managed by considering various hardware design options involving digital signal processing chips, array processors, host microprocessors, and host supervisory computer.

The program involved four major tasks:

- Strain-gage data bank compilation
- Modular classifier development
- Software specification
- Hardware specification.

This report summarizes the technical effort involved in the exploratory study. The major effort was directed toward the accomplishment of the first two tasks (data compilation and classifier development) and the rest of the effort toward the definition of overall software and hardware system specifications.

In Section 2.0, various types of aeromechanic phenomena and noise will be reviewed and in Section 3.0 the compiled strain-gage data base will be discussed. A thorough description of the strain-gage data classifiers will be given in Section 4.0 with representative analysis results discussed in Section 5.0. The software and hardware system specifications that have evolved based on the classifier structure will be described in Sections 6.0 and 7.0 respectively. The conclusions and recommendations are made in Section 8.0.

2.0 AEROMECHANICAL RESPONSES AND NOISE

An in-depth physical understanding of various aeromechanical phenomena that have been observed and recorded in previous compressor testing is required in designing a computer controlled on-line vibratory stress monitoring system. The more thoroughly we understand the physical phenomena, the more successfully we can derive the strain-gage signal classification criteria. The reliability of a stress monitoring system not only depends on its capability of identifying active aeromechanic phenomenon but also rests on its ability in rejecting unwanted noise that creates large signals. In this section, various kinds of aeromechanical phenomena will be discussed first, followed by a description of noise unrelated to blade vibrations.

2.1 Aeromechanical Phenomena

The aeromechanical phenomena discussed below include flutter, resonance and off resonance forced vibration, separated flow vibration, rotating stall and surge, rotor or stator tip rub, and unlatched stator vane.

2.1.1 Flutter

Flutter is a self-excited unstable motion of the blade caused by a net unidirectional energy flow from the passing airstream into the compressor blade. The frequency of flutter vibration is usually not an integral multiple of the engine rotational frequency, though integral order flutter may occassionally occur. Figure 1 shows typical strain gage responses associated with a high-speed torsional flutter condition. In deep flutter all blades vibrate at the same frequency and the interblade phase angle is fixed as shown in Fig. 1. It is generally safe to back off the flutter boundary by reversing the operating conditions the test vehicle went through earlier when approaching the flutter boundary.

2.1.2 Resonance and Off-Resonance Forced Vibration

Resonance is a periodic damped motion of blades excited by a periodic aerodynamic forcing function whose frequency matches the blade natural frequency. The possible sources of resonant vibration are inlet distortion, structural struts, instrumentation, burner cans or nozzles among others. The blade response frequency is necessarily an integral multiple of the engine rotational frequency. Figure 2 shows typical resonance stress growth with speed change. An example waveform of resonant vibration containing strong 4 engine order and weak 2 engine order responses is shown in Fig. 3. The waveform of resonant vibration in general stands still on monitor scopes with scope sweeps triggered by the engine per-rev signal. Resonant vibration can be cleared by either decel or accel of the test vehicle.

2.1.3 Separated Flow Vibration

Separated flow vibration, also called buffeting, is an irregular damped motion of the blades excited by turbulence in the flow field. It usually shows as a multimode (i.e., multi-frequency) response with amplitude varying randomly in time. It often occurs toward the stall line or before stall flutter occurs. Typical responses are shown in Fig. 4.

2.1.4 Rotating Stall and Surge

As the flow through an axial compressor is throttled from the design point to the stall limit, the steady, axisymmetric flow pattern that exists becomes unstable. The phenomenon resulting from this instability can take one of two forms. These are known as surge and rotating stall (Ref. 5). The two types of behavior are illustrated schematically in Fig. 5. Surge is a large amplitude oscillation of the total annulus averaged flow through the compressor; whereas in rotating stall, one finds from one to several cells of severely stalled flow rotating around the circumference, although the annulus averaged mass flow remains constant in time once the pattern is fully developed. The frequencies of surge oscillations are typically over an order of magnitude less than those associated with the passage of the rotating stall cells, and, in fact, during a surge cycle, the compressor may pass in and out of rotating stall as the mass flow changes with time. Examples of strain-gage rotating stall and surge responses are shown in Fig. 6.

To the compressor test engineers, it is important to know which of these modes of instability occurs during stall since their consequences can be quite different. For example, once rotating stall is encountered, it may not be possible to return to an unstalled condition merely by opening the throttle, because of system hysteresis effects. In this situation, the only way to come out of stall may be to decrease rotational speed considerably, resulting in a sizeable loss in pressure ratio. Also, because of the extremely low efficiencies associated with the presence of rotating stall (efficiencies below twenty percent have been measured) operation for any substantial length of time in this mode can result in excessive internal temperatures which have an adverse effect on blade life, as do the large stresses resulting from the unsteady flow field. In addition, an even more serious consequence that can occur in an engine is that the low flow rates obtained during rotating stall can lead to substantial overtemperatures in the burner and turbine.

On the other hand, if surge occurs, the transient consequences, such as large inlet overpressures, can also be severe. However, the circumstances may well be more favorable for returning to unstalled operation by opening either the throttle or internal bleeds, since the compressor can be operating in an unstalled condition over part of each surge cycle. For this reason, it is important to know which of these two types of behavior occurs during compressor stall.

2.1.5 Rotor or Stator Tip Rub

This usually occurs once (or rarely, several times) per rotor revolution due to obstruction(s) originating from the casing or hub. A typical waveform of tip rub would show kick-in stress once per revolution as shown in Fig. 7. Rubbing is often, though not always, a self-clearing phenomenon.

2.1.6 Unlatched Stator Vane

Occassionally, a vane may become loose due to either control system malfunction or severely bent lever arm. The off-angle of the loose vane may be large enough to cause the neighboring rotor blades to respond with one-per-rev type spikes. The response would appear to have much larger amplitude variation than the tip-rub response.

The major characteristics of various kinds of aeromechanical phenomena are comparatively shown in Table 1. The columns of Table 1 corresponding to the eight vibration phenomena under study are denoted by the following abbreviations:

RES = Resonance
FLT = Flutter
SFV = Separated Flow Vibration
VAN = Misrigged or missing vane
ROT = Rotating stall
SRG = Surge
RUB = Blade Rub
NRV = NonResonant Forced Vibration

The rows of Table 1 correspond to nine general characteristics exhibited by the vibration phenomena. From these qualitative characteristics, specific quantitative features can be defined, and will form the basis for the classification algorithms. In Table 1, amplitude refers to any measure of vibration level such as peak amplitude, RMS value, percent modulation or similar value. Phase refers to the phase of a single blade vibration waveform with respect to some reference point on the circumference of the compressor casing. Frequency content refers to the modal composition together with forcing frequencies as measured by a FFT, a set of tracking filters, or some other means. Signature refers to the distinctive shape of the time envelope of the vibration, such as a beat phenomenon or rub decay. Interblade refers to the degree of involvement of all the blades on a single stage in the vibration phenomenon. Interstage refers to the degree of involvement of multiple stages in the vibration phenomenon. Looks-like refers to these phenomena which exhibit similar characteristics to the phenomenon in question. Occurs-with refers to those phenomena which can occur simultaneously, precede or follow the phenomenon in question. Speed refers to the dependence of the phenomenon on engine speed or engine transients.

Table 1 can be refined as additional data is examined, and additional experience of knowledgeable technical personnel is imparted. The characteristic key or index in Table 1 is used to indicate the likelihood that the stated characteristic is true. The itemized characteristics in Table 1 constitute the baseline information needed for the classifier development to be discussed in Section 4.0 and 5.0.

2.2 A Brief Account of Noise

Noise is defined as any apparent strain-gage response that is unrelated to actual blade vibrations. It is desirable during compressor testing to isolate noise from true aeromechanical responses so that testing can proceed with no unnecessary interruption. Because there are many possible sources of noise, either identifiable or unidentifiable, the classification of noise is at least as challenging as that of true aeromechanical responses. Discussed below are those types of noise that are better understood and considered most important in the overall noise category of strain-gage responses.

2.2.1 Line Noise

Line noise originates from power source and always has frequency of 60-Hz and/or higher harmonics.

2.2.2 Slip Ring Noise

The slip ring noise is primarily due to poor brush contact (mechanical slip ring). Initial deterioration of the slip ring assembly creates one-per-rev type strain-gage response. As time progresses, grass look responses would arise. In any case, the signal is usually one sided and generally occurs for blades linked to the same deteriorated slip ring.

2.2.3 Telemetry Noise

The telemetry noise is generally one-per-rev or two-per-rev in nature depending on the telemetry system design. The noise level remains relatively constant as speed changes.

2.2.4 Open and Short Circuit Noise

Open circuit can be caused by strain-gage grid separation or disconnection of electronic instruments and usually produces one sided saturated strain-gage signal. Short circuit can be caused by insulation breakdown of strain-gage grid or electronic components and generally produces zero apparent strain level.

2.2.5 Supersensitive Gage Noise

Sometimes, strain gages show large responses similar to flutter or resonance when the actual strain level is low. A full understanding of this unusual phenomena has not been achieved. It is probably caused by local necking down of strain-gage grid wire resulting in discontinuous stress distribution along the grid wire. Sometimes, it can be identified when a substantially higher (say five times) stress level is encountered during testing while the same gage did not experience as high a stress level in previous testing at the same operating condition. The supersensitive gage noise is exceptionally difficult to identify and requires further study to discriminate it from flutter or resonance signals.

2.2.6 Intermittent Noise

Intermittent noise could be caused by electrical disturbances such as switch or cross talks between strain-gage wires, slip ring wires and scope wires due to poor shielding. It can also be caused by mechanical disturbances such as cable whip. It is characterized by nonstationary random bursts of high intensity signals.

In Table 2, the noise characteristics are tabulated for easy reference. It appeas that the identification of noises is as challenging as classifying true aeromechanical responses.

3.0 STRAIN-GAGE DATA BASE

The strain-gage data used in this program was digited from Pratt & Whitney analog tapes. The analog data were recorded in previous test programs for Energy Efficient Engine (E^3) compressor, TS22 fan, F100 fan and compressor, and J52 compressor.

3.1 Data Categories

The data base includes 345 digital signals that correspond to the following vibration types for various test vehicles:

Resonance - E^3 (18)
Flutter - TS22 (32)
Separated flow vibration - E^3 (45)
Misrigged vane - F100 (46)
Rotating stall - E^3 (48)
Surge - TS22 (17), F100 (33)
Tip rub - J52 (35)
Noise - E^3 (36)
Mixed - E^3 (35)

Each piece of digital signal is approximately 1 minute long. The nominal digitizing rate is 5120 Hz (i.e., analyzable frequency range of 2 kHz) with a block size of 4096 points for a duratiaon of 0.8 sec. Some surge and rotating stall data, tip-rub data and noises were also digitized at 25.6 kHz to yield an analyzable 10-kHz bandwidth.

A substantial collection of noise data were digitized. But the identification of the noise types associated with those data would require additional effort. Consequently the noise detection modules have been designed solely based on the expected noise characteristics listed in Table 2.

3.2 Digital Tape Format

The data were delivered to UTRC from P&W on tapes written by a PDP-11 machine. This tape is a 9-track, 800 bpi, ASCII tape. Each block on the tape contains 4096 words.

The P&W tapes were read by a Sperry 1100 program and the data were rewritten to a 9-track, 6250 bpi binary tape for input to the UTRC's Interactive Signal Processing Program (ISPP).

3.3 Data Format

Each file on a tape contains strain-gage data of a single phenomenon from three or four strain gages. A file is structured in blocks of 4096 integer data values. The first block contains header information and RMS values for the three strain-gage sensors and speed or four strain-gage sensors. The following blocks contain data from the three strain-gage sensors and speed or four strain-gage sensors in sequence.

Figure 1 shows the structure of the tape.

Figure 1. Tape Data Structure

Block No.	Words	Contents
1	1 - 499	Header information
	500 - 999	RMS SG1
	1000 - 1499	RMS SG2
	1500 - 1999	RMS SG3
	2000 - 2499	RMS N1 or SG4
	2500 - 4096	Empty space
2	1 - 4096	SG1 data
3	1 - 4096	SG2 data
4	1 - 4096	SG3 data
5	1 - 4096	N1 or SG4 data
6	1 - 4096	SG1 data
7	1 - 4096	SG2 data
8	1 - 4096	SG3 data
9	1 - 4096	N1 or SG4 data
.		
.		
.		

3.4 Data Retrieval

Data from the tape can be read into ISPP using the input mode or using the strain-gage classifier tape option in the process mode.

To use ISPP input mode, NBEG, the beginning data sequence number, NUMB, the number of contiguous sequences to input, NSKP, the number of contiguous sequences to skip and, NREP, the number of repetitions must be input. (Ref. ISPP users manual.)

The beginning data sequence number is calculated by the equation

$$(NB-1)*4 + (SG+1)$$

where

NB = no. of the strain-gage block to be read in

and

SG = strain-gage number (i.e., 1, 2, 3 or 4)

The number of contiguous sequences to input is the number of contiguous strain gage blocks of data to input.

The number of contiguous sequences to skip is calculated by the equation

$$(NS*4) - NUMB$$

where

NS = no. of strain-gage blocks to skip for a given strain gage

and

NUMB = number of contiguous sequences to input (entered above)

The number of repetitions is the number of times the input and skip options are repeated.

For example, if blocks 5, 10 and 15 for the 1st and 2nd strain gage on a file are to be input NBEG = 18, NUMB = 2, NSKP = 18 and NREP = 3.

To use the strain-gage classifier tape option only one strain-gage data block is read in at a time. The strain-gage number and the block number are the only input necessary.

4.0 STRAIN-GAGE CLASSIFIER DESCRIPTION

The strain-gage signal classifier, SG Classifier, should be designed as an on-line monitoring system capable of processing up to 100 strain-gage signals in real time. Real-time operation means the processing of all incoming strain-gage signals without data interruptions, and the reporting of processing results within a maximum delay time interval of, say, two secs. This requires the buffering of incoming strain-gage data while previous data is being processed. To accommodate all compressor types the SG Classifier needs to be designed as a generic "expert" program with all compressor dependent parameters confined to an external data file. It also needs to be designed to utilize most of the on-line operational information and a priori information that is available to an experienced test cell engineer. The operator interface has to be interactive with unambiguous prompting and error messages. Several levels of SG Classifier descriptive output should be available under operator control.

In this section, a thorough discussion of the classifier structure evolved in this research program will be given. The discussion will emphasize the development aspect of the classifier. Therefore, many considerations are only necessary for the training of the classifier and are not required for online system implementations.

4.1 Classifier Design Principals

4.1.1 Multilevel Classification

The aeromechanical phenomena to be detected are distributed both spatially and temporally. To best match this physical situation a three level classification algorithm has been developed. The first level is the individual strain-gage classification level. Each strain gage is processed independently using global featues extracted from its vibration signal. No explicit structural or operational information is used at this level. The output of the first level is a set of pseudoprobabilities or quality values (Q) along with corresponding features for each of the aeromechanical phenomena.[§] The Q values range from zero to unity, with zero indicating the strain-gage signal does not match the phenomenon, and unity indicating a perfect match. The output from the first level of classification is stored according to strain gage in an external file called the spatial file. The first level of classification is complete when all contemporaneous

[§]The Q values are pseudoprobabilities because they do not sum to unity across the eight phenomena. Moreover, they are not derived from an underlying probability distribution function. However, for simplicity the prefix pseudo will be dropped in the remainder of the text.

strain-gage signals have been processed and their corresponding Q values stored in the Spatial file.

The second level of classification is spatial combination. The individual strain-gage results stored in the Spatial file are combined with compressor structural information and on-line operational information to produce event probabilities for the phenomena. The event probabilities are stored in the Event file.

The third level of classification is temporal combination. The event probabilities stored in the Event file are combined with on-line operational information, off-line a priori information and data from other sensors to produce final or running probabilities for the phenomena. The final probabilities are reported to the operator and are updated after each event.

4.1.2 Modular Design

The first classification level is modular in structure. Each aeromechanical phenomenon to be detected has a corresponding category detection module. The independence of the category detection modules allows for straightforward addition of new modules or alteration of existing modules. The structure of individual modules is kept simple by the use of global features which are extracted outside the modules and are common to all the modules. The internal structure of the modules is thus limited to the computation of a few, if any, module specific features together with simple inferential (If, Then, Else) or relational (And, Or, Greater-than) statements.

4.1.3 Degradation Logic

The computation of probabilities at all three classification levels is accomplished using soft decision logic. Most of the featues upon which the probabilities are computed have finite precision, including those features ordinarilly thought of as being binary (present or not present). For example, integral-order is a commonly used binary feature to differentiate resonance and flutter phenomena. However, a strict binary decision is not advisable because the accuracy of the integral-order computation is limited by the time-bandwidth product of the measurement and the uncertainty introduced by the nonstationarity of the phenomenon over the measurement interval. All features, binary or continuous, have a nominal value which is considered ideal for the phenomenon in question. Any deviation from the nominal value should be penalized such that the probability of the phenomenon is degraded. Without degradation logic a binary decision would result in a Q value of zero if the required feature were "absent" even though the feature was close to being present. With degradation logic the Q value determination is softened to allow for a margin of error.

The algorithm used for Q value determination is,

$$Q = \mathrm{MAX}\left(0.,\ 1.0 - \sum_{i=1}^{N} W_i d_i \quad \sum_{i=1}^{N} W_i\right)$$

$$d_i = \left(\frac{\mathrm{error}_i}{D_i}\right)^{e_i}$$

$$\mathrm{error}_i = \begin{cases} -\mathrm{MIN}(0.,\ F_i - FN_i) & \text{if Mode} = -1 \\ |F_i - FN_i| & \text{if Mode} = 0 \\ \mathrm{MAX}(0.,\ F_i - FN_i) & \text{if Mode} = 1 \end{cases}$$

where:

N = number of features
W_i = weight of ith feature
d_i = degradation due to ith feature
D_i = normalization divisor for feature i error
e_i = exponential degree for feature i error
F_i = actual value of ith feature
FN_i = nominal value of ith feature

$$\mathrm{Mode} = \begin{cases} -1 \text{ to penalize only if } F_i < FN_i \\ 0 \text{ to penalize if } F_i \neq FN_i \\ 1 \text{ to penalize only if } F_i > FN_i \end{cases}$$

A particular category detection module will use N features in the computation for the probability value Q. Each feature will have a nominal value representing either the ideal value or the expected value for that feature. In the case of binary features the nominal value is either 0 or 1. When the strain-gage signal is processed a numeric value for the feature F_i is computed and compared to the nominal value FN_i. There are three modes for computing the error. For mode 0, any deviation of F_i from FN_i is treated as an error. For mode 1, only a deviation where F_i exceeds FN_i is treated as an error, otherwise the error is zero. For mode -1, only a deviation where F_i is less than FN_i is treated as an error, otherwise the error is zero. The error is normalized by the divisor D_i so that it falls within the nominal range of 0.0 to 1.0. The normalization step compensates for different units of measurement. The normalized error is

raised to an exponent e_i to realize a particular error criterion. A linear error criterion is realized with e_i equal to 1. A quadratic error criterion, which penalizes large deviations more heavily than small deviations, is realized with e_i equal to 2. The exponentiated normalized error for feature i is referred to as the degradation due to feature i. A weighting value W_i associated with each feature is used to adjust the relative importance of the feature. A weight of zero indicates that the feature is not to be used in the determination of the probability. A relative large value of W_i indicates that the feature is critical.

The probability value Q is computed by subtracting from unity the ratio given by the sum of the weighted degradations divided by the sum of weight values. Ideally, if all the d_i were in the range from 0. to 1., then Q would be in the range of 0. to 1. However the actual value of d_i may exceed unity due to the open-ended range of the computed feature, thus giving a negative Q value. To prevent this, Q is limited to a minimum value of zero.

4.1.4 Global Features

Perhaps the most critical step in the SG Classifier design is the specification of the feature set. If the feature set is flawed or incomplete then the classifier will yield poor results. The specification of the feature set must take into account three requirements:

(1) the feature set must be complete,
(2) qualitative features must be quantified,
(3) redundant features must be eliminated.

The feature set is assembled by studying a table of characteristics, such as Table I, and formulating appropriate deterministic or statistical measures for each characteristic. Often a characteristic is defined in qualitative terms such as "sinusoidal". In these cases, a mathematical equivalent to the qualitative description must be developed. Lastly, to prevent the classifier from being biased toward particular characteristics, redundant features must be eliminated. For example, if two features were 100% correlated then the equation for the category probability indicates that the same probability could be obtained by using one of the features and doubling the feature weight. Now if the features were in fact dependent the net result would be to erroneously weight the feature at twice its importance.

The characteristics of the aeromechanical phenomena given in Table I can be divided into three groups: individual strain-gage characteristics, spatial characteristics and temporal characteristics. The individual characteristics include integral order determination, sinusoidal purity, number of frequency peaks and amplitude behavior. The spatial characteristics include phase

coherence, interblade involvement and interstage involvement. The temporal characteristics include speed dependence and syntactic relationships.

A vast assortment of numerical and statistical measures exist to quantify the above characteristics, such as correlation values, coherence functions, various transforms, modulation indices, probability density functions and various statistical moments. From these measures an infinite number of features can be defined. However to prevent feature redundancy and to minimize execution time the SG Classifier feature set has been limited to:

(1)	Stress features:	Simple stress measures extracted directly from the strain-gage signal.
(2)	FFT features:	Frequency and phase information extracted from the complex Fourier transform of the strain-gage signal.
(3)	Histogram features:	Statistical measures of amplitude distribution.

Notably absent from the feature set are correlation and coherence functions. This information is either directly available from the above features or can be readily derived. A detailed description of the feature set is given in the Classifier Structure section.

4.2 Classifier Data Acquisition and Data Flow

The SG Classifier continuously monitors the incoming strain gage signals and processes these signals whenever either a stress threshold on an instrumented part is exceeded or a specified performance regime is entered. This latter monitoring mode is required to detect the onset of rotating stall or surge. Once a monitoring condition is reached, data is acquired from all strain gages, not just those exceeding threshold. The strain-gage data as well as tachometer data are input in digitized blocks of data via direct memory access to assigned memory locations in the SG Classifier's host computer.

4.2.1 Data Acquisition

The data acquisition format is shown in Fig. 8. Each strain gage is coupled to dedicated signal conditioning and digitizing hardware. The SG Classifier processes data in blocks of 4096 data points. The time interval of a data block is dependent on the sampling rate. The SG Classifier will accept any sampling rate, but practical limitations dictate a range from 1024 Hz to 25600 Hz. The nominal sampling rate has been designated to be 5120 Hz. Table 3 lists the processing limitations associated with the various sampling rates. At 5120 Hz

the 4096 point data block spans an interval of 0.8 secs, giving a frequency resolution of 1.25 Hz. The highest discernable frequency is 2560 Hz which corresponds to 12 engine orders at 12,000 rpm.

The maximum of 100 strain gages require a dedicated 400K words of random access memory in the host computer. For greatest speed the data blocks and tachometer signal should be transferred via direct memory access. Prior to processing, the data should be compensated by the appropriate scale factor to correct for gain attenuations during data acquisition.

4.2.2 Data Flow

The processing of the strain-gage data is illustrated by the data-flow diagram in Fig. 9. At a given point in time there are N strain-gage data blocks to be processed. The number N corresponds to the number of strain-gage sensors that have been instrumented, up to a maximum of 100. The index I denotes that strain gage I is currently being processed. The N data blocks, referred to as the event, are synchronized by the data acquisition system and are registered in time with respect to the tachometer pulse sequence. The SG Classifier computes engine speed and accurately determines a timing pulse for phase reference.

The classifier sequentially processes all N data blocks. For each data block a number of global features are computed and stored in the Spatial File. The data block along with the global features are then passed to the category detection modules. Each module computes a probability value Q which is the quality of fit of the data to the phenomenon being detected. The probability values and features from each module are stored in the Spatial File.

After all N data blocks comprising the event have been processed, the event probabilities are computed and stored in the Event File, the Spatial File is reinitialized and the classifier proceeds to the next event. As the processing of events continues the probability of the currently active phenomenon will grow to near unity, while the probabilities of the other phenomena will decay to small values. At this time either a manual or automatic procedure can be invoked to take corrective action.

4.3 Strain Gage File

The SG Classifier is a generic classifier applicable to all compressors. All information regarding the particular compressor being tested and its associated instrumentation is contained in an external file referred to as the SG File. The SG File also stores intermediate processing results from the SG Classifier. Because of the high degree of interaction between the SG Classifier and the SG File the latter must be a random access file with an efficient data

base management system for storing, retrieving and altering the data. A tree type data structure was developed to meet the SG File requirements.

4.3.1 Basic Tree Structure

Two tree structures representing minimum and maximum storage overhead are shown in Fig. 10. Each tree is composed of intermediate nodes and terminal nodes. The actual data values in the SG File are stored at the terminal nodes. The intermediate nodes contain pointers to successor nodes and represent file overhead. The maximum depth of the SG File has been set to 8 nodes. The size of the SG File including overhead is from 2 to 3 times the number of data values contained within. The minimum overhead case, illustrated in Fig. 10a, occurs for a one level tree. This is a trivial case which defeats the advantages of a tree structure. The maximum overhead case occurs when all nodes branch into two successors giving a binary tree structure as shown in Fig. 10b. The number of values in the binary tree is $M = 2^{\ell}$ where ℓ is the number of levels, excluding the root level. The total number of nodes in the tree is 3M-2, excluding the root node. For a large binary tree, $M >> 1$ and the ratio of nodes to values approaches the maximum value of 3. A typical tree structure will have an overhead of about 2.5.

4.3.2 Data Storage and Retrieval

Data in the SG File is accessed by specifying the tree address of the data, as opposed to the actual file address of the data. An example of a simple tree structure showing tree addresses and the corresponding file structure is given in Fig. 11. Six data values are stored in the tree (in this case the tree storage overhead is 2.5). The tree address of any data value is easily determined by noting the branch number at each tree level required to reach the data value. The sequence of branch numbers is the tree address of the data value. For example, to reach data value V_D, one must follow branch 1 from level 0, branch 3 from level 1 and branch 2 from level 2; thus giving a tree address of 1,3,2 for V_D. The actual file address of V_D is location 11. The location of V_D in the file is found by using the tree address indices as relative addresses into the file. For example, the file address is initially 1; adding the first tree address index of 1, and subtracting 1 gives a file address of 1, which contains the quantity 3. Now because there are remaining tree address indices yet to be used, the algorithm treats the contents of file location 1 as a pointer into the file. The file address is updated to the pointer value of 3. Adding the next tree address index of 3 and subtracting 1 gives a file address of 5, which contains the quantity 8. Again, since there is one additional tree address index to be processed the quantity 8 is taken to be a pointer and the file address is updated to the pointer value of 8. Adding the last index of 2 and subtracting 1 gives the file address 9. Since no additional tree address indices remain, the

contents of file address 9, which is the value 11, is taken to be a pointer to the data value V_D. Thus V_D is found at file address 11.

Although the above procedure is tedious to perform manually, it is efficiently performed automatically by the function SGFVAL which returns a data value given its tree address. For example,

```
VALUE = SGFVAL (IER, IADDR, 1,3,2,0,0,0,0,0)
```

returns the value V_D in the variable VALUE and the file address of V_D in the integer variable IADDR. If an error is encountered in tracing the tree address indices then the IER integer variable will be set to the index at which the error was encountered.

For general data storage and retrieval the subroutines SGFPUT and SGFGET are used. These routines store or retrieve a contiguous sequence of data values at a specified SG File address. The SG File address is obtained using the SGFVAL function. For example,

```
CALL SGFPUT(SGFILE, IADDR, DATA, ND, IPR, LENGTH)
```

will store the sequence of data values of length ND located in array DATA into the SGFILE starting at location IADDR. The data values are listed by setting IPR to unity. The dimension of SGFILE is specified in the argument LENGTH.

4.3.3 SG File Construction

The construction of the SG File is accomplished in two steps. First the SG File Skeletal Structure is defined and then the data values are loaded. The skeletal structure is defined by specifying the number of branches at each tree node. This is accomplished using the subroutine SGFBLD, which interactively prompts the user for the required information on a node by node basis. The output of the SGFBLD subroutine is a functional SG File whose data values are initially all zero. The next step is to load the SG File with the desired data values using a succession of SGFVAL and SGFPUT subroutines. For efficiency it is recommended that the SGFVAL and SGFPUT subroutines be grouped into blocks which represent related information. An entire block can then be submitted in one step to load the corresponding portion of the SG File. This is especially convenient when switching between compressor types which may entail the changing of over one hundred parameters. An example of a compressor data block is given in Fig. 12.

4.3.4 SG File Structure

The SG File has three major components, the Information file, the Spatial file and the Event file, as shown in Fig. 13. The Information file contains all operational and structural information that must be specified prior to SG Classifier operation. The Spatial and Event files store the intermediate processing results obtained during SG Classifier operation. The skeletal structure of the Spatial and Event files must be specified prior to operation. The detailed structure of the three files is defined below.

4.3.4.1 Information File

The Information file comprises the first branch of the SG File and is denoted by tree address 1,0 as shown in Fig. 13. The four major subdivisions of the Information file are denoted Operational, Structural, Strain Gage and Run Options, as detailed in Figs. 14-18.

As shown in Fig. 14, the Operational subdivision contains test identification descriptors, control sequence timing information, data acquisition information and P/WA tape data base format information (used for classifier development and not for final implementation). The address of each node is specified along with the number of branches at each node (the encircled quantity). There are 3 locations for cell identification, 3 for test identification, 5 for control sequences, 10 for data acquisition and 40 for tape format. The cell identification and test identification locations are for descriptive purposes and will be listed with SG Classifier output. Each of the control sequences contains the specification of a control change such as acceleration or vane positioning that occurs during the course of the compressor test. This information, if specified, is primarily for off-line postprocessing of strain gage data, and is used to reconstruct the test scenario. For on-line processing the compressor control changes are input directly to the classifier as they occur. A control change specification consists of the time of occurrence, control type and subtype and the magnitude of the change. The data acquisition information consists of sampling rate, block size, coupling method, number of channels, time slew between channels, strain gage sensitivity and various gain values. The tape format information given in Table 4, is supplied for classifier development and refers to the typical strain gage data base contained on magnetic tape.

The Structural subdivision shown in Fig. 15 contains information specific to the compressor being tested including, compressor identification, accumulated run hours, known problems, number of rotating and nonrotating members, number of struts, bleed holes and auxiliary instrumentation probes, stress thresholds and natural frequencies of the compressor components. This information is specified with respect to a generic compressor structure shown in Fig. 21. The generic

structure is defined in terms of rotor or stator units starting at the front of the compressor. The unit specification is more general than the usual rotor/stator stage specification, and allows for cases where two or more stators precede a rotor.

The compressor identification information includes compressor type, subtype, maximum RPM and other limit values. The probability and priority information permits known problems to be identified to the classifier on a category by category basis. For example, if a particular compressor was prone to stall then the initial probability of the rotating stall and surge categories could be increased. For each compressor unit the information specified includes unit type (rotor or stator), blade or vane type (such as axial or circumferential dovetail), number of parts per unit, various threshold values for the part and mode information (bending or torsional, nominal frequency, frequency tolerance and bandwidth). The remainder of the Structural information consists of the number and location of all the struts, bleed holes and auxiliary probes.

The Strain Gage subdivision shown in Fig. 16 contains identification and location information on every instrumented strain gage. As shown in Figs. 22 and 23 the location information consists of the unit number, part number, location on the part and grid orientation. The location on the part is specified by surface location (convex or concave), radial location (root to tip) and chord location (leading to trailing edge). The grid orientation is important in determining the strain gages ability to measure bending versus torsional vibrations. The strain-gage identification includes type, linearity, saturation level and response bandwidth.

The Run Options subdivision shown in Figs. 17 and 18 contains all adjustable parameters which effect the operation of the classifier. The subdivision is further divided into groups of parameters for each of the classifier subroutines. The various parameters offer a large degree of flexibility in the operation of the classifier. Most of the parameters are of use primarily during the developmental stages of the classifier and would not need to be accessible in the final implementation. Specific information on the parameters will be given in the Classifier Structure section.

4.3.4.2 Spatial File

The Spatial File shown in Figs. 13 and 19 is the second branch of the SG File and is denoted by tree address 2,0. The Spatial File stores classifier results from the tachometer and each of the strain gages within a single time interval. The tachometer data is processed by the classifier resulting in compressor RPM and other speed related quantities which are stored in the left-hand branch of the Spatial File. The righthand branch contains three major subdivisions for each strain gage: Location information, Common information and Category information. The Location subdivision contains the same information for

the strain gage as found in the Information file. This information is copied over when the strain-gage data block is processed. The Common subdivision contains all the global features extracted from the strain-gage data block including threshold features, stress features, histogram features and FFT features. The Category subdivision contains the processing results of all the category detection modules, namely the probability values and the extracted features. The contents of the Spatial File will be explained in more detail in the Classifier Structure section.

4.3.4.3 Event File

The Event File shown in Figs. 13 and 20 is the third branch of the SG File and is denoted by tree address 3,0. The Event File stores the classifier results for each event. Recall that an event corresponds to the spatial combination of the individual strain-gage results stored in the Spatial File. The Event file contains three major subdivisions for each event: Timing information, Operational information and Category information. The Timing subdivision consists of the time the event occurred, engine speed, pressure ratios, etc. The Operational subdivision consists of the time of the last control input prior to the event, control identifiers and the magnitude of the control change. The Category subdivision consists of the computed probabilities for each of the vibration categories.

4.4 Classifier Structure

The computational units of the SG Classifier are organized in a structured framework of subroutines diagrammed in Fig. 24. The leading subroutine SG calls the subroutines SGSPD, SGTHR, SGGLB, SGM, SGEVT and SGFIN, to perform the tasks of tachometer processing, data thresholding, global feature extraction, module probability determination, event probability determination and final probability determination. The SGGLB subroutine calls the subroutines SGGHST, SGGSTR and SGGFFT to compute histogram, stress and FFT global features respectively. These subroutines are independent and could be performed in parallel. The SGM subroutine calls the category subroutines SGMRES, SGMFLT, SGMSFV, SGMROT, SGMSRG, SGMRUB, SGMNIN, SEMNSR and SGMNOS for the detection of resonance, flutter, separated flow vibration, rotating stall, surge, rub, intermittent noise, slip ring noise and open-short noise respectively. These subroutines are also independent and could be performed in parallel. There is no explicit subroutine for detecting a misrigged vane. This problem is defined by its effects on other compressor stages and is detected in subroutine SGFIN. The following paragraphs specify in detail the parameters required, the computations performed and the output produced in each of the SG Classifier subroutines.

4.4.1 SG Subroutine

The flow diagram for subroutine SG given in Fig. 25 shows the functional steps involved in the computation of the category probabilities. Prior to running the SG Classifier the test engineer must supply the classifier with structural information as discussed previously in the SG File section, and must specify various classifier run options. The run options give the test engineer considerable flexibility in processing the strain-gage data. This flexibility is primarily of use during classifier development but a number of the run options will also be included in the final implementation.

Classifier execution begins with the initialization of the Spatial and Event files which will contain the classifier processing results. Classifier results are computed using all information back to the last initialization time. For off-line classifier development the user is prompted for strain-gage data at every time epoch, at which time the user can elect to reinitialize the files. For on-line operation the user will not be prompted, but can invoke the initialization process at any time via an interrupt command.

For on-line operation the strain gage data for one event (4096 data points from each instrumented strain gage) is input via direct memory access into the SG Classifier memory. For off-line operation the data is input from magnetic tape via subroutines SGTAPE and SGINP. The time duration of the event will be from about 0.2 secs to 6 secs depending on the sampling rate. At the nominal 5120-Hz sampling rate the event will be 0.8 secs in duration. For on-line operation the SG Classifier will input directly all control and auxiliary sensor data. For off-line operation the SG Classifier will input this data from the Information file, assuming the data is available.

Engine speed and timing information is decoded in subroutine SCSPD using the tachometer pulse sequence that accompanies the strain-gage data. All of the strain-gage data for the event is referenced to the trailing edge of the first tachometer pulse, thus allowing phase relationships to be computed. Any time slew that may exist between the strain-gage data channels is assumed to be compensated prior to data input to the classifier.

The SG Classifier processes each strain-gage data block individually and stores the results in the Spatial file. The index I in Fig. 25 indicates the specific strain gage being processed. The data is first compared to the stress threshold corresponding to the blade or vane type, in subroutine SGTHR. If the data exceeds the threshold or if the classifier is in the monitor mode then the classifier computes global features in subroutine SGGLB and computes category probabilities in subroutine SGM.

After all N strain gages have been processed the classifier computes the event probabilities in subroutine SGEVT by combining the individual strain-gage probabilities with compressor structural information. The event probabilities are then stored in the Event file and the Spatial file is cleared to accept the next event. For on-line operation the final probabilities are computed by subroutine SGFIN automatically as each event is processed by combining the event probabilities with on-line compressor operational information. For off-line operation the computation of the final probabilities is under user control. The output of classifier results is also under user control and can be as simple as a single category decision or a complete listing of features and intermediate computations leading to the decision.

4.4.2 SGSPD Subroutine

The flow diagram for subroutine SGSPD is given in Fig. 26. The subroutine requires the sample frequency (SMPFRQ) and the maximum compressor RPM (RPMAX), and computes the average RPM over the data block interval. In addition the percent RPM (PRPM), the number of tachometer pulses (NCNT), and the locations of all tachometer pulses, including the first (NTIC) and last (NTICL), are computed.

A typical tachometer signal is shown in Fig. 47. For noise immunity the SGSPD subroutine computes and subtracts the DC-value plus 60% of the peak value from the signal, prior to locating negative going transitions. The RPM and PRPM are computed by

$$RPM = NREV*SMPFRQ*60/NUMB$$

$$PRPM = RPM/RPMAX$$

where

NREV = NCNT-1
NUMB = Number of samples in NREV revolutions.

Figure 26 gives the addresses in the SG File where the required parameters are obtained and the computed values are stored. For example the locations of all the tachometer pulses (up to 200) are stored in tree addresses 2,1,2,1,0 through 2,1,2,200,0.

4.4.3 SGTHR Subroutine

The flow diagram for subroutine SGTHR is given in Fig. 27 (see also Table 6A for the definition of parameters). The subroutine requires several scaling

parameters and a stress threshold value. The output includes a corrected strain-gage data block and the sample number at which the threshold value is exceeded (ITH). Several options exist for scaling the input data: no scaling, multiplication by a given scale factor, and multiplication by a computed scale factor based upon data acquisition gain values available in the SG File. The latter method is used in correcting the off-line tape data stress units to units of PSI. An option also exists to compute and subtract the average stress level.

The threshold value is dependent on the compressor unit on which the strain gage is instrumented. This provides flexibility in specifying different thresholds for different blade and vane types. The corrected strain-gage data is compared to the threshold value and ITH is set to the sample number at which the threshold is first exceeded. If the data does not exceed threshold, then ITH is set to zero. The SG Classifier has a run option (tree address 1,4,5,4,0) which governs whether threshold exceedance is required before the data is processed further. In the monitor mode this run option is set to unity allowing all strain-gage data to be processed regardless of threshold exceedance.

4.4.4 SGGLB Subroutine

The flow diagram for subroutine SGGLB is given in Fig. 28. The subroutine requires several synchronization parameters (NSYNC, NTIC and ITH) and several feature extraction flags (OPTS, OPTH and OPTF). The function of the SGGLB subroutine is to call the three global feature extraction subroutines SGGSTR, SGGHST and SGGFFT. The strain-gage data is synchronized under user option NSYNC to either the first data sample, the trailing edge of the first tachometer pulse (NTIC) or the threshold exceedance sample (ITH) of the first strain gage to exceed threshold. The three feature extraction subroutines can be selectively disabled by setting the appropriate flag(s) to unity.

4.4.4.1 SGGSTR Subroutine

The SGGSTR subroutine (Fig. 29) extracts various stress features from the complete data block and from subintervals of the data block. The subroutine requires two parameters NBIN and MAXBIN (see Table 5) which define the number of subintervals and the maximum allowable subintervals respectively. On the complete 4096 sample data block, SGGSTR locates the first three largest stress values (STRP, STR2, STR3) and their corresponding sample numbers (NTRP, NTR2, NTR3). The value STR3 is usually a more reliable value for peak stress than is STRP because the latter is more likely to be associated with a wild data point. SGGSTR also computes the average stress (STRA), the RMS stress (STRR), the peak to RMS ratio (SINE) and the sum of squares or power (SUM) over the complete data block. The peak to RMS ratio is often used to discriminate sinusoidal from non-sinusoidal signals. In the former case the ratio will have the value of $\sqrt{2}$. For a constant signal the ratio will be unity and for a random noise signal the ratio will be approximately 3 or above.

The length of the subintervals is determined by NPSG/NBINS where NPSG is nominally 4096. For each subinterval the peak stress (STRP), the RMS stress (STRR), the average stress (STRA) and the peak to RMS ratio (SINE) are computed. The variation of each of these values over the subintervals is then computed using,

$$\text{variation} = \frac{\text{max value} - \text{min value}}{\text{max value}} \,.$$

The computed variations are stored in VARP, VARR, VARA and VARS respectively. The variation values are measures of the stationarity of the strain gage signal over the data block. A limit cycle phenomenon such as flutter will usually be stationary over the time interval represented by one data block (nominally 0.8 seconds), and will thus give a small variation value from 0. to 0.1. An impulse type phenomenon such as surge will produce large fluctuations in stress over the data block, giving a variation value from 0.8 to 1.0. Table 6A summarizes all the stress features that have been considered. An illustration of the waveform stress features is given in Fig. 48.

The gross stress features are stored in the spatial file in locations (2,2,ISG,2,3,1,0,0) to (2,3,ISG,2,3,14,0,0). The subinterval stress values are stored in the spatial file in locations (2,2,ISG,2,4,J,1,0), where ISG is the strain gage order number and J is the subinterval index.

4.4.4.2 SGGHST Subroutine

The SGGHST subroutine (Fig. 30) extracts stress probability density features from the histogram of the data block. The subroutine requires four parameters NBIN, MODE, VMIN and VMAX (see Table 6B) which define the number of abscissa intervals (bins) and the domain of the abscissa (stress axis) on the histogram. For MODE = 0 the SGGHST subroutine determines the minimum and maximum stress values in the data block and uses these values to define the histogram. For MODE = 1 the VMIN and VMAX values supplied in the Information file will be used. This latter option insures uniformity between histograms from different data blocks for comparison purposes. The number of histogram bins (NBIN) determines the coarseness of the histogram. Too few bins corresponds to heavy smoothing which obscures the fine structure of the underlying probability density function (pdf). Too many bins corresponds to little or no smoothing which gives a noisy estimate of the pdf. For the nominal 4096 samples per data block a satisfactory histogram is obtained for NBIN between 100 and 500.

The histogram is computed by subroutine HIST and the features are extracted by subroutine MMTHST. The shape of the histogram is used to discriminate deterministic phenomena from random phenomena. For example, certain noise signals give rise to skewed probability distributions. A typical histogram is shown in Fig. 49.

The features extracted from the histogram consist of the mean, median, mode, variance, standard deviation, second, third and fourth central moments, skewness, kurtosis and the 99th, 98th, 95th, 90th and 80th percentiles. The normalized mean stress value is computed from the histogram by,

$$MN = \sum_{J=1}^{NBIN} J*HIST(J)/NPSG$$

where NPSG is the total number of samples in the data block and HIST(J) is the number of stress values in bin J. The normalized mode is computed by,

$$MD = J, \text{ where } HIST(J) > HIST(I) \text{ for all } I \neq J.$$

The second, third and fourth central moments are computed by,

$$MC(K) = \sum_{J=1}^{NBIN} HIST(J)*(J-MN)**K/NPSG \text{ for } K = 2,3,4.$$

The variance and standard deviation are,

$$VAR = NPSG*MC(2)/(NPSG-1)$$

$$SDV = VAR**0.5.$$

The skewness and kurtosis are computed by,

$$SKW = MC(3)/MC(2)**1.5$$

$$KUR = MC(4)/MC(2)**2.$$

The median and percentile values are computed by

$$PER(L) = K, \text{ so that } \sum_{J=1}^{K} HIST(J) = \frac{L*NPSG}{100} \quad \text{for } L = 50, 80, 90, 95, 98, 99,$$

where the median value is PER(50).

The actual stress values are computed from the normalized features by,

$$VALUE = \frac{VMAX - VMIN}{NBIN} * \text{Feature} + VMIN,$$

for the mean, median, mode and percentile values; and

$$VALUE = \text{Feature} * \left(\frac{VMAX - VMIN}{NBIN}\right) ** K,$$

for the central moments. The skewness and kurtosis features are normalized quantities by definition and do not require correction. An example of histogram feature extraction is shown in Fig. 50.

The histogram features are stored in the spatial file in locations (2,3,ISG, 2,5,1,0) to (2,2,ISG,2,5,19,0), and are summarized in Table 6B.

4.4.4.3 SGGFFT Subroutine

The SGGFFT subroutine (Fig. 31) extracts frequency domain features from the magnitude of the FFT (periodogram) of the data block. The periodogram is an estimate of the power spectrum of the data block. Smoothing is generally required because the periodogram is not an efficient estimator.

The SGGFFT subroutine requires five parameters, NBEG, NEND, NDC, NFFT, and MWND (see Table 5). NBEG and NEND define the first and last data samples to be used in computing the FFT, thus providing the capability of computing the FFT over a particular subinterval of the data. NDC specifies that the average stress value shall be computed and subtracted from the data block prior to the FFT. NFFT specifies the length of the FFT as a power of two. If NFFT exceeds the number of samples NUMB, equal to NEND-NBEG+1, then the remaining values will be zero-filled. If NFFT is less than NUMB then NFFT is adjusted to the power of two greater than NUMB. This procedure permits the use of a computationally efficient power-of-two FFT algorithm. The MWND parameter specifies the window function which will be applied to the data block prior to the FFT. Data windowing is a procedure for reducing power spectrum estimation errors resulting from data truncation. Two window options are provided; MWND = 1 selects the Hamming window and MWND = 2 selects the Hanning window. After applying the above parameters the complex FFT of the data block is extracted, and the magnitude and phase sequences are computed.

The FFT features are extracted by subroutine FFTPKS shown in Fig. 32. The subroutine uses two parameters, NBINS and PLEVEL, for a degree of automatic gain control on the extracted features. This is accomplished by computing all feature values relative to the noise power level of the data block. The noise power is estimated from the histogram of the power spectrum (periodogram) by noting that a typical power spectrum contains a broad-band noise level combined with a number of signal peaks (Fig. 51). The histogram is an estimate of a Rayleigh-type distribution and will have the characteristic shape shown in Fig. 52. Most of the frequency components will have a stress value in the noise level which is located toward the left on the histogram abscissa. The user can specify a percentile PLEVEL (typically 0.8 to 0.9) which defines the noise power threshold VNOIZ.

Two types of features are extracted from the FFT periodogram; gross features such as total power and noise power, and peak features which are particular to each spectral peak. The number of spectral peaks is determined by the peak threshold THRPK. THRPK can be specified either as an absolute level or relative to the noise power VNOIZ. If multiple peaks are extracted they are ordered according to decreasing power content. The features extracted from each peak, as listed in Table 6C, include the frequency, magnitude, phase, bandwidth, power, percent power, engine order and blade mode correspondence.

The feature NPK is the frequency sample number of the spectral peak, and FREQ is the corresponding frequency. VPK is the peak stress magnitude. VPHS is the phase associated with sample NPK and is determined by the phase sequence computed from the FFT. NWL is the lower bandwidth of the peak expressed in samples, and is measured at stress threshold THRBWL. The threshold THRBWL can be

specified either absolutely, relative to VN01Z or relative to VPK. NWU is the upper bandwidth expressed in samples and is measured at stress threshold THRBWU, which is specified like THRBWL. APK is the sum of squares of stress values within the lower bandwidth NWL, and is a measure of the power at that particular frequency peak. SPK is the equivalent sinusoidal amplitude that would produce APK. EPK is the ratio of APK to the total sum of squares (TPOWER). RAPK is the ratio of APK to the sum of power values for all the extracted spectral peaks. RACC is the cumulative power for the current and previous peaks with respect to the sum of all spectral peaks. EO is the engine order as determined by FREQ/RPS. IO is an integral order flag, and is nonzero only if FREQ is within a specified tolerance of an integral multiple of RPS; otherwise IO is zero and FERR is set to the error. IMODE is the mode number of the closest mode, and FMODE is the corresponding modal frequency. FMERR is the modal error in units of modal bandwidths, and is set to zero if FREQ is within one bandwidth of the nominal mode frequency. MTYPE is the type of modal vibration, such as bending or torsional. A typical FFT periodogram with corresponding features is shown in Fig. 53.

The gross power features are stored in Spatial file locations (2,2,ISG,2,1,1,0,0) to (2,2,ISG,2,1,9,0,0). The peak features are stored in locations (2,2,ISG,2,2,J,1,0) to (2,2,ISG,2,2,J,19,0) where J is the peak index. The features are summarized in Table 6C.

4.4.5 SGM Subroutine

The SGM subroutine (Fig. 33) contains the category detection modules. The modules are executed sequentially in the order RES, FLT, SFV, ROT, SRG, RUB, NIN, NSR and NOS. The category detection modules are mutually independent and require only the strain-gage data block and the global features for inputs.

4.4.5.1 SGMRES Subroutine

The SGMRES subroutine (Fig. 34) detects resonance phenomena. Recall from Table 1 that resonance is characterized by an integral order, sinusoidal vibration, usually corresponding to a single mode. However multimodal resonances do occur and must be accounted for. Similarly, a resonance mode can be excited by a subharmonic excitation in which case the vibration waveform will exhibit a regular modulation pattern characterized by subharmonic integral order frequencies.

The SGMRES subroutine requires the FFT global features, PKS, BWL, EPK, RAPK, FERR, IO and FMERR. The subroutine first checks the number of FFT peaks (PKS) and degrades the probability value Q if PKS is greater than 1. The largest energy peak (the only peak if PKS = 1) is then examined for other resonance characteristics as follows. The peak must contain 50% or more of the vibration

energy, must be integral order, must correspond to a blade mode and must have a bandwidth of one frequency resolution cell. The category Q is degraded if any of these conditions is not satisfied. For multiple peaks, the sum of the energies in the peaks (RAPK) must exceed 80% of the total energy, and all peaks must be integral order.

The amount of degradation contributed by a particular feature is governed by the degradation constants discussed in section 4.1.3. The nominal degradation constants for resonance are contained in the Information file starting at location (1,4,7,2,1,1,1,0), and listed in Table 7. These values have been determined empirically and can be adjusted periodically as warranted by additional data.

4.4.5.2 SGMFLT Subroutine

The SGMFLT subroutine (Fig. 35) detects flutter phenomena. Recall from Table 1 that flutter is characterized by a nonintegral order sinusoidal vibration which is usually a single mode, and usually the first torsional mode.

The SGMFLT subroutine requires the FFT global features IO, PKS, EPK, BWL, FMERR, IMODE and MTYPE. First the subroutine checks the integral order flag IO and sets the Q to zero if IO is nonzero (integral order). If IO is zero, the subroutine checks for a single peak containing 50% or more of the energy, having a bandwidth of one sample and corresponding to the first torsional mode. The nominal degradation constants are given in Table 7 starting at location (1,4,7,2, 2,1,1,0).

4.4.5.3 SGMSFV Subroutine

The SGMSFV subroutine (Fig. 36) detects separated flow phenomena. Recall from Table 1 that separated flow vibration is characterized by a random modulation of a blade mode, usually the first bending mode, and is nonintegral order.

The SGMSFV subroutine requires the FFT global features IO, BWL, IMODE, FMERR and MTYPE. If the vibration is integral order then Q is set to zero. If the vibration is nonintegral order then the level of random modulation is gaged by the bandwidth of the main energy peak, and the frequency of the peak is compared to the blade modes. The nominal degradation constants are given in Table 7 starting at location (1,4,7,2,3,1,1,0).

4.4.5.4 SGMRUB Subroutine

The SGMRUB subroutine (Fig. 37) detects blade rubbing. Recall from Table 1 that a rub vibration is characterized by a one-per-rev excitation which excites a first bending or first torsional mode. However, the signature of the vibration

varies widely with the circumferential extent of the excitation. In looking at a single data block, the only generalizations are that the rub vibration will usually exhibit multiple peaks, with one peak being first engine order and one peak corresponding to a blade mode, usually first bending.

The SGMRUB subroutine requires the FFT global features EO, IO, FERR, IMODE, FMERR and MTYPE for all peaks. The subroutine processes each peak and computes the minimum engine-order error (EOERR) and the minimum modal error (FIERR). If no peak has IO = 1 then the Q value is degraded using EOERR. Similarly, the Q value is degraded if a blade mode is not detected. The nominal degradation constants are given in Table 7 starting at location (1,4,7,2,7,1,1,0).

4.4.5.5 SGMROT Subroutine

The SGMROT subroutine (Fig. 38) detects a rotating stall. Recall from Table 1 that a rotating stall is characterized by the stall cells impacting the part. When the frequency of these impacts coincides with a modal frequency, resonance occurs. The resonance can be either integral or nonintegral order.

The SGMROT subroutine requires the FFT global features PKS, BWL, EPK, IMODE and FMERR. Since a rotating stall looks like a resonance phenomenon, it is detected as such. The nominal degradation constants are given in Table 7 starting at location (1,4,7,2,5,1,1,0).

4.4.5.6 SGMSRG Subroutine

The SGMSRG subroutine (Fig. 39) detects a surge phenomenon. Recall from Table 1 that a surge is characterized by a short duration, high intensity vibration having a heavy first bending mode content. The impulse nature of the surge excites many blade modes and produces a wide spectral bandwidth.

The SGMSRG subroutine requires the FFT global features PKS, IO, IMODE, FMERR and MTYPE. In addition, the global stress feature VARP is used as a measure of nonstationarity. The impulse nature of the surge implies that the surge is nonstationary and nonintegral order. Thus if IO is nonzero then the Q value is set to zero, and if VARP is less than the nominal value of 0.8 then the Q is degraded. The Q is further degraded if the main energy peak does not correspond to the first bending mode. The degradation constants are given in Table 7 starting at location (1,4,7,2,6,1,1,0).

4.4.5.7 SGMNLN Subroutine

The SGMNLN subroutine (Fig. 40) detects line noise. Line noise is characterized by 60-Hz frequency and/or its higher harmonics and is detected as such.

4.4.5.8 SGMNSR Subroutine

The SGMNSR subroutine (Fig. 41) detects slip-ring noise. Slip-ring noise is characterized by one-per-rev noise bursts usually on one side of the stress signal. The subroutine requires the FFT global features EO, BWL, BWU, IMODE and FMERR, and the histogram global feature SKW.

The subroutine first checks the main FFT peak against the known blade modes and sets the Q value to zero if a correspondence is found. If the main peak is not first engine order the Q value is degraded. The randomness of the slip-ring noise is checked by the upper and lower bandwidths, BWU and BWL. The one-sided nature of the noise is checked by the skewness (SKW) of the histogram. The nominal degradation constants start at location (1,4,7,2,9,1,1,0).

4.4.5.9 SGMNTE Subroutine

The SGMNTE subroutine (Fig. 42) detects telemetry noise. Telemetry noise is characterized by two-per-rev (i.e. 2E) sinusoidal wave form but in general the 2E frequency does not correspond to the blade frequency except at resonant condition. The subroutine requires the FFT features EO and FMERR for the largest peak of FFT spectrum. The 2E frequency is checked by the engine order EO and the separation from the blade modal frequency is checked by the feature FMERR.

4.4.5.10 SGMNOS Subroutine

The SGMNOS subroutine (Fig. 43) detects open or short circuits in the strain-gage instrumentation. An open or a short circuit is characterized by the signal either saturating or going to zero at random times for arbitrarily long durations. The subroutine requires the stress value SINE for all subintervals of the data block. If the value of SINE (which measures the peak to RMS ratio) is equal to unity in any subinterval then the stress value is a constant in that interval, which is tantamount to an open or short condition. The nominal degradation constants start at location (1,4,7,2,10,1,1,0).

4.4.5.11 SGMNIN Subroutine

The SGMNIN subroutine (Fig. 44) detects intermittent noise. Intermittent noise is characterized by nonstationary bursts of high intensity. The subroutine requires global stress features, STR3, SINE and VARP. The STR3 value is the third largest value in the data block, and thus is an indicator of the high intensity noise bursts. It is used instead of the peak value STRP because of the ever present possibility of data outliers, as discussed earlier. The SINE feature is a measure of randomness, and the VARP feature is a measure of nonstationarity. The nominal degradation constants start at location (1,4,7,2,8,1,1,0).

4.4.5.12 SGEVT Subroutine

The SGEVT subroutine (Fig. 45) combines the individual strain-gage results stored in the Spatial file and computes the event probabilities for the current time epoch. This computation incorporates the interblade and interstage features given in Table 1. The subroutine requires the run options NUNFB, PSLO and PSHI which are used to define the front and back regions of the compressor, and the percent-speed high and low values. The subroutine also requires Q values, location information and global features from all strain gages stored in the spatial file. The specific features used are ITH, STR3, STRR, FPK, VPK, VPHS and SPK.

The SGEVT subroutine first combines the individual Q-values from each strain gage by selecting the maximum Q-value for each category using all the strain-gage results. This form of combination is justified for several reasons. First, for many phenomena the individual part vibrations are highly correlated. For example a stage resonance implies that all parts are at (or near) resonance. However, due to slight variations in the resonance frequencies of the parts, certain parts will be at resonance while other parts will be slightly off resonance. The Q-values for the strain gages will reflect this variation, with certain gages giving a Q for resonance of, say 0.95, while other gages give a resonance Q of say 0.70. In this case, the high Q value is the more reliable indicator of resonance. A second reason for selecting the maximum value is due to the absence of an underlying probability density function which would be required to optimally combine the Q values. Finally, if the Q values were combined as though they were independent then the resulting Q values would be unrealistically high. For example, suppose eight strain gages had Q values of 0.2 then the overall Q (assuming independence) would be 0.84.

The SGEVT subroutine next determines the number of compressor units NUINV that have been instrumented with strain gages, and the number of units NUTHR having at least one part exceeding threshold. IF NUINV is unity then spatial combination cannot be performed since there is no way of knowing whether the phenomenon is confined to the single instrumented unit.

If more than one unit is instrumented the subroutine checks the number of units actually exceeding threshold. For a single unit exceeding threshold, if all the parts on the unit are involved (exceed threshold) then the ITOTB flag is set to unity. In addition, a check is made on adjacent instrumented units to determine if there exists a low level blade response matching the frequency of the dominant unit. If such a match is found the adjacency flag IADJ is set to unity. For multiple unit involvement, the ITOTUN flag is set to unity if every instrumented unit is involved. The involvement is checked to see whether it is confined to the front or back of the compressor, as determined by the NUNFB parameter, and if so the IFRONT or IBACK flag is set to unity.

The Q values for the individual categories are degraded using the spatial features described above. For resonance, the Q is degraded if multiple units are involved or, in the case of axial dovetail mounted blades, if not all instrumented blades on the unit are involved. For flutter, the Q is degraded if multiple units are involved or if not all instrumented blades on the unit are involved. For rub, the Q is degraded if multiple units are involved. For surge the Q is degraded if any instrumented unit is not involved. For rotating stall the Q is degraded if no adjacent stage is involved at a low level. For separated flow vibration the Q is degraded if the unit involvement is not confined to the front (back) of the compressor at low (high) speed. The above degradations are incorporated in the computation of the event probabilities, which are then stored in the Event file.

4.4.5.13 SGFIN Subroutine

The SGFIN subroutine (Fig. 46) combines the event probabilities stored in the Event file with on-line transient information to compute running, final category probabilities. This computation, referred to as temporal combination, incorporates the "occurs-with" and "speed dependence" features given in Table 1.

As each event is processed by the SGEVT subroutine the event probabilities along with on-line control information are stored in the next available location in the Event file. The SGFIN subroutine compares the new event to the preceding event and if no engine control changes have occurred the new event probabilities are combined with the preceding probabilities using a maximum selection rule, and the new event is discarded. If a control change is detected then the new event remains stored and no combination with the previous event is performed. If a speed change has occurred and the present maximum Q value compared with the previous maximum Q value indicates that a unit has moved onto or off of a resonance condition then the resonance Q value is increased to the value $Q_{NEW} = 1-(1-Q_{OLD})^2$, the assumption being that the two events are independent and have equal Q values. Finally, if multiple units are represented in the event file and if the maximum Q on each unit corresponds to flutter or resonance, then a vane problem is likely to be the cause. The unit having the vane problem can be localized by noting the location of the affected units. The running probabilities are reported to the operator along with as much, or as little, supporting information as desired.

5.0 EXAMPLES OF SIGNAL CLASSIFICATION

Detailed stress waveform features, histogram features and FFT features were computed on UNIVAC computer for selected strain-gage signals each of which is 0.8 sec long. These signals include flutter, resonance, surge, misrigged vane, separated flow vibration, and rotating stall.

5.1 Typical Processing Results

Typical strain-gage waveforms, FFT plots, and histograms for various phenomena are shown in Figs. 54 through 62. In each of these figures, the waveform for a 0.8 sec time interval is shown in block (a) and an expanded waveform for a substantially shorter time interval is shown in block (d) for clarity. The FFT spectrum and the histogram for the 0.8-sec data are shown in blocks (b) and (c) respectively.

A typical waveform of fan flutter is shown in Figs. 54(a) and 54(d). The flutter frequency is 640 Hz and a stress amplitude modulation persists as the speed is held at 8000 rpm. Figure 55(b) shows two waveforms of which the lower one corresponds to a low-stress, before-resonance 1E response at about 11265 rpm and the upper one corresponds to a high stress 5E resonance at 11419 rpm. Note that the low stress 1E component due to possibly a misrigged vane persisted during the accel, but does not introduce significant stresses in this case. The flutter waveform as shown in Fig. 54(d) indicates some random amplitude modulation, while the resonant waveform as shown in Fig. 55(d) exhibits an orderly and repetitive amplitude variation. This apparent waveform distinction can probably be used as an indicator of flutter when flutter frequency happens to be of integral order (a rare but realistic situation).

Figure 56(d) shows three episodes of separated flow vibration response taken during a slow accel around 9500 rpm. The dominant response frequency is 480 Hz. The stress amplitude varies significantly and randomly from one episode to another and maintains a relatively constant level within each episode. This specific pattern of amplitude modulation is a useful feature for distinguishing separated flow vibration from flutter.

Figure 57(a) shows the stress experienced by a vane in a multistage compressor during a surge event with participating rotating stall responses at 12000 rpm. The low frequency (below 5 Hz) surge cycle as shown in Fig. 57(a) can be physically associated with axial flow reversal. Over the surge cycle, the blade oscillates at its natural frequency slightly below 300 Hz as shown in a expanded time scale in Figs. 58(a) through (d). The amplitude variation of the blade natural vibration through the surge cycle can be attributed to the rotating

stall cell(s) passing through the blade at a frequency of about 90 Hz (about half of the rotational frequency). By examining the waveform, a dc shift of the stress signal appears significant for the surge event and may prove to be useful in alarming the occurrence of surge.

A typical surge waveform without rotating stall cells is shown in Fig. 60(a) and (d). After the initiation of surge, the blade responds at its natural frequency near 700 Hz with fluctuating amplitudes similar to separated flow vibrations.

A typical tip rub waveform is shown in Fig. 61 with the one-per-rev pulses. The apparent on-per-rev amplitude envelope is due to the blade tip rub against a fixed spot on the engine case. Unfortunately the digital tip rub data were improperly handled and can not be processed to yield quantitative information in the frequency domain and the histogram domain. However, it can be argued that the frequency content of tip rub signals should not have 1E response in general. Instead, the dominant frequencies should be $f_{rotation} \pm f_{blade}$ where $f_{rotation}$ is the rotor rotational frequency and f_{blade} is the blade natural frequency.

A typical misrigged vane induced stress waveform is shown in Fig. 62(a) and (d). It is essentially an integral order resonance response of fluctuating amplitude. The most dominant response is at the 16E frequency as shown in Fig. 62(b).

In block (c) of Figs. 54 through 62, typical histograms for all vibration types are shown. It is seen that the histograms for surge and rotating stall (Figs. 57 and 60) have significantly sharper peaks than flutter, separated flow vibration, resonance, and misrigged vane. (Figs. 54, 55, 56, 62.) Hence, kurtosis, a measure of peakiness of the histogram, is used as a feature in the vibration detection modules.

5.2 Calculated Probability Values

The formula for pseudo-probability calculations as discussed in Section 4.0 requires feature values and empirical constants (weight factors, nominal feature values, error normalization divisors, error exponents and mode constants) as inputs. The empirical constants given in Table 7 were selected so that the computed pseudo-probabilities become consistent with the majority of the strain gage signals in terms of vibration types.

The probabilities of selected strain-gage signals representing resonance, flutter, separated flow vibration, misrigged vane, rotating stall. and surge,

have been computed. Representative results are given in Table 8. The highest probability values appear to match the known phenomena of the test signals very well except about half of the rotating stall signals could have been interpreted as tip rub signals. Further adjustment of the degradation constants and/or the introduction of more features would be needed to yield more consistent matching between signals and vibration detection modules.

6.0 SOFTWARE SYSTEM SPECIFICATIONS

6.1 Software Configuration Overview

6.1.1 Operational Requirements

The strain-gage classifier is designed to be an on-line monitoring system capable of processing up to 100 strain-gage signals in real time and predicting in prevailing aeromechanic condition. All incoming signal events are to be processed within a maximum delay of 2.0 seconds. In addition, the classifier is designed to be independent of all compressor types. The strain-gage classifier utilizes on-line operational information and a priori information that is available to an experienced test cell engineer. Other operational requirements include system modularity to facilitate upgrades, minimum response time for evasive action to an abnormal condition, control of data transfer between the host computer and the peripherals, and interactive operator interface with unambiguous prompting, error messages, and operator selective output.

6.1.2 Hardware Environment

On-line Hardware Environment

The on line hardware system is illustrated in Fig. 63. The acquisition modules convert electrical sensor inputs to digital speed and stress values. These data are reduced by an array processor providing stress global feature information. The host supervisory computer classifies and displays the current aeromechanic phenomenon utilizing the global feature values. The raw data and/or calculated features are recorded on digital magnetic tape for further off-line data reduction. An abnormal or emergency condition will cause a facility evasive action from the supervisory computer.

The on-line software system resides within both the array processor and the host supervisory computer. The host supervisory computer serves as an operator interface for test function management, classifies and displays the data, and monitors engine safety. The array processor performs data acquisition and front end processing. This combination of hardware is necessitating by the real time performance requirements. Refer to the hardware description for performance details

Off-line Hardware Environment

The hardware environment of the off-line software system is shown in Fig. 64. Since the off-line system operates on the recorded data, the real time

processing requirement is removed and the need for the array processor is eliminated.

6.1.3 Software Environment

Software development will use support libraries native to the system on which it will ultimately run. System memory and peripheral capacity will be sufficient to support the software development environment and the execution of the specified tasks and subtasks.

On-line Software Environment

The hardware components suggest that there exists a natural division of responsibilities among the software components. As mentioned, the host computer performs classification and management functions while the array processor performs data acquisition and global feature extraction. Software for the host shall be developed using ANSI-FORTRAN 77. Development for the array processor software will depend on the language and support libraries associated with that array processor in order to achieve the necessary computational speed. The host computer will serve as the development system for the array processor; the program will then be downloaded to the array processor's program memory. The array processor processes data from x number of channels, the number of channels depending on the particular array processor chosen (refer to the hardware description for more details). Figure 65 illustrates the overall software flow diagram.

Off-line Software Environment

Software of the off-line system shall also be developed in ANSI FORTRAN 77 but shall use support libraries of the host computer only.

6.1.4 System Methods

Programming Languages

All programs and subprograms developed shall be written in ANSI standard FORTRAN 77. The only general exceptions will be peripheral device drivers and integration software which shall be written in assembly language. The computer operating system shall be capable of multiple tasking.

Programming Mnemonics and Constants

Program mnemonics for variable and subprogram names reflect their function and/or meaning in relation to the classification procedure. A list of variables

used for the global features may be found in Tables 6A, 6B and 6C. Degradation constants used for the computation of probabilities are listed in Table 7.

Internal Documentation

All programs and subprograms developed for the strain-gage software system shall contain detailed documentation containing the following information:

1) Program name and purpose.

2) List of calling programs and supporting subprograms.

3) Initial date of development.

4) Record of program modification dates and explanation of modification.

5) Explanation of usage and contents of data contained in argument lists and common storage.

6) General discussion of procedures performed.

7) Explanation of possible error conditions and checks.

6.2 On-Line Software Components

6.2.1 Host Software

The host processor is responsible for the final strain-gage signal classification and for the overall management of test functions. The software system which reside within the host is designed to operate in three distinct and mutually exclusive modes, i.e., pretest, test, and post-test mode. Figure 66 shows the host on-line operational modes with their corresponding tasks and subtasks. The Strain-Gage Software System (SGSS) shall perform the task of classifying strain-gage data both on-line and off-line, but within two different physical environments as described above (Section 6.1.3).

Pretest Mode

Operation in pretest mode allows the system operator to perform all test setup procedures. Prior to running the strain gage classifier, the operator must supply the compressor structural information and the classifier run option described in Figs. 17 and 25.

Test Mode

Test mode operation is entered upon the completion of all pretest mode tasks. This mode provides two tasks, i.e., the health diagnostic task and the supervisor task.

The health diagnostic task (safety monitor) performs periodic checks of test vehicle performance parameters against specified limits. During any critical condition, the alarm or evasive actions shall be accessed. Various subtasks (data acquisition, edit, calibration, display, test done) may be operator selective within the supervisor task.

Selection of the data acquisition subtask puts the array processor in the ready state, then triggers the acquire-process activity. The computer inputs from the array processor, global feature data which characterize each strain gage. These data are combined with spatial and temporal information (compressor specific information and run time parameters) to complete the classification. The host computer calls the subroutines SGM, SGEVT, an SGFIN to perform the operations of category probability determination, event probability determination, and final probability determination. After all strain-gage data have been processed by SGM, the Classifier computer the event probabilities in subroutine SGEVT by combining the individual strain-gage probabilities with compressor structural information (spatial combination). For on-line operation the final probabilities are computed by subroutine SGFIN automatically as each event is processed by combining the event probabilities with on-line operational information temporal combination. The output results are then displayed within 2.0 sec after initial data acquisition.

Choosing the edit subtask for execution will allow the system operator to review recorded data. Data will be acquired from the tape, processed and displayed as if it were real-time data.

Data display formats may be selected by the operator from within the display task. This includes the selection of channel(s), stage(s), FFT results or probability Q value(s) from the category, event, and/or the final probability determination calculations.

These tasks and subtasks within the test mode will function on an interrupt-driven basis. Subtasks within the supervisory task may be activated and/or deactivated on keyboard command and may be temporarily suspended by the health diagnostic (Safety Monitor) task.

At any point during test mode, the system operator may choose to execute a system calibration subtask. This subtask allows the system operator to alter the

values of an assortment of hardware parameters such as sample rate, amplifier gain, or filter cutoff frequency within the hardware acquisition subsystem.

Test mode operation may be terminated with the selection of the test-done subtask.

Post-Test Mode

The post-test mode of operation is entered immediately following the end of the test mode. This mode allows the system operator to use data recorded on magnetic tape or disk as input for the off-line data reduction system.

6.2.2 Array Processor Software

The array processor is responsible for the real-time acquisition of strain-gage data and for global feature extraction. The front end processing performed by the array processor is illustrated in Fig. 67. The two modes of operation for the array processor, pretest and test, are diagrammed in Fig. 68 along with their tasks.

Pretest

The pretest mode accomplishes the system initialization within the array processor. Program instructions are transferred from the host system to the array processor program memory and the data reflecting the operating parameters is transferred to the array processor data memory.

Test

The test mode of operation is entered upon triggering by the host. This mode provides the real time data acquisition/processing task. Strain-gage data for one event (nominally 4k) is input from x channels to the array processor and processed. Subroutines SGSPD, SGTHR, SGSTR, SGHIST, and SGFFT are used for tachometer processing, data scaling/thresholding, stress analysis, histogramming and FFT calculations. Data acquiring, processing, and outputting to the host is to be accomplished within 0.8 second for x number of channels. The number of channels depends on the particular array processor selected. Refer to the hardware description for more details on the array processor.

Engine speed and timing information is decoded, using the tachometer pulse sequence that accompanies the strain-gage data. All of the strain-gage data for the event is referenced to the trailing edge of the first tachometer pulse, thus allowing phase relationships to be computed.

6.3 Off-Line Software

6.3.1 Comparison With On-Line Software

The basic features of the off-line system software are very similar to those of the on-line system. The major dissimilarity results from the fact that the off-line system is not required to function in real time. This has an immediate effect on the particular hardware environment for software execution. Without the restricting throughput time, the host computer would be capable of performing the front end calculations as well as the classification. Figure 69 illustrates the host's off-line operational modes and tasks.

Classifier execution begins with the initialization of run options and compressor information during the pretest mode. Classifier results are computed with respect to the last initialization time. For off-line classifier development the user is prompted for train gage data for every time epoch.

The off-line system is not required to access data in real time. Instead, the data is input from magnetic tape via subroutines SGTAPE and SGINP. The operator may be selective in the order and content of data read by the off-line system. Data may be processed out of chronological sequence by the off-line system. For a 2 byte data word and a maximum data rate of 10240 Hz, input from 38 channels may be stored on an off-line tape ((6250 bytes/inch x 125 inches/sec)/20480 bytes/sec/channel). Three tapes would be required in order to store data from all 100 channels. Approximately 3 minutes of storage is acquired with a tape of 145MB capacity (145MB/(781KB/sec x 60 sec)).

The signal processing algorithms employed by the off-line system may be designed to produce more accurate results than the on-line system. The operator may have more freedom in choosing the length of the time series to be processed and the type of data windowing to be used.

The test mode provides the selection of the process task, display task, or the done task. For off-line operation, the computation of the final probabilities is under user control. The output of classifier results (performed by the display task) is also under user control and can be as simple as a single category decision or a complete listing of features and intermediate computations leading to the decision. Finally, test mode operation is terminated with the selection of the test-done task.

6.4 Software Quality Assurance

Quality assurance test procedures will follow the functional classifier design described above. Each software component/module will be tested individually prior to testing the fully integrated system.

7.0 HARDWARE SYSTEM SPECIFICATIONS

7.1 Hardware Configuration Overview

7.1.1 Critical Instrumentation Design Issues

In addition to providing modularity and testing flexibility, the strain-gage classifier must meet a certain set of requirements and performance goals. These requirements used to define the instrumentation hardware include the following: (1) processing up to 100 strain-gage channels in real time; (2) displaying the predicted prevailing aeromechanical phenomena within two seconds; (3) providing evasive action within one second for vehicle protection against unstable mechanical or aeromechanical conditions; (4) being compressor independent; and (5) recording data on tape for off-line analysis.

7.1.2 Approaches

Design criteria adopted for meeting the objectives as previously stated include cost, time constraints, accuracy, modularity, practicality, future expansion, and hardware/software trade-offs.

In order to maintain modularity, each channel will have a signal conditioner, digitizer, and buffer. The size of the buffered data block is dependent on the sampling rate. Although any sample rate is possible, practical limitations require as range between 2560 Hz to 10240 Hz with an 0.8-second data block. The 0.8-sec data block allows sufficient time for evasive action within one second and a final throughput within two seconds. The nominal sampling rate has been designated to be 5120 Hz. At this frequency, 4096 data points are acquired over the 0.8-sec interval giving a frequency resolution of 1.25 Hz. The highest discernible frequency at this rate is 2560 Hz which corresponds to 12 engine order at 12,000 rpm.

Figure 65 illustrates the overall flow of software calculations to be performed by the strain-gage classifier. These were previously defined in Section 4.0. The global features are calculated for each channel and combined with those from the other channels for probability determinations. For the maximum 100 strain gages, 400 k of data (4k x 100 gages) is input and processed by the front end and approximately 7500 values (75 x 100 gages) are output. Based on this I/O, several options for a hardware configuration were considered.

In one option, a very powerful computer would be needed in order to process the 400 k of data and provide a final throughput time of 2 seconds. More practical considerations, however, dictate the need for parallel processing. Front end preprocessing would be performed by an array processor(s), a computer or special

hardware. The preprocessing involves acquiring the buffered data, scaling it for conversion to engineering units, and calculating certain global features (stress, histogram, and FFT). This is illustrated in the front-end processing block diagram (Fig. 67). Operations in parallel to the front end, a supervisory minicomputer would combine the calculated features along with spatial and temporal information, i.e., compressor specific information and certain run time parameters to predict the active aerodynamic phenomena.

Various design options involve the use of an array processor or the equivalent for calculating the global features. A survey of front-end feature extractors was conducted using the following baseline parameters: (1) 4k of buffered data per channel; (2) 5120-Hz sampling rate; (3) 100 strain gages; and (4) approximately 75 values output from each channel to the category detection modules.

The use of a powerful microprocessor for the front-end calculations was rejected due to its speed limitations. The possibility of using a special digital signal processing chip such as the TMS320 or its second generation version from Texas Instrument was researched. As shown in Fig. 70 (Option I), this would provide system modularity on a per channel basis. Although the chip itself is fairly low cost, extra program and data memory would be needed as well as special hardware interfacing. Speed and memory limitations arise as the sample rate increases beyond the nominal 5120 Hz. In addition, all programming would be on the assembly language level.

A second option, depicted in Fig. 71 (Option II), would incorporate an array processor (AP) such as Sky or Marinco for each channel. This approach provides for modularity, speed, and future expandability; however, a microprocessor is needed as a host for the AP thus making this a costly approach. These AP's are also programmed using a low level language or limited function calls.

Another design consideration as illustrated in Fig. 72 (Option III) involves a slightly more powerful array processor such as Mercury, Analogic or the second generation Sky for processing x number of channels. The actual number of channels depends on the particular AP selected but varies from 15 to 20. This method provides modularity, speed, future expansion and is reasonable in cost. It has the capability of accommodating increased sample rates or throughput times by simply calculating over less channels. In addition, the Mercury and Analogic AP's run stand alone once they are down loaded with the program.

A final approach uses a very powerful array processor such as Numerix, Floating Point Systems or CSPI in order to process 50 or 100 channels per unit. For this approach, x would be 50 or 100 in Fig. 72. This design requires a high initial investment and is not modular on a per channel basis. However,

the array processor may be programmed with a high level language such as Fortran.

The following subsection describes the final system design configuration.

7.1.3 Final Overall Hardware Configuration

The Strain-Gage Hardware System (SGHS) will be integrated with the Strain-Gage Software System (SGSS) to form the complete Strain-Gage System. It will perform all the functions necessary to acquire data from up to 100 strain gages, to process the data, to display the results on viual monitors and to develop a tape for off-line analysis. Using hardware Option III (Fig. 72), the conceptual block diagram for the SGHS shown in Fig. 73, consists of three main areas: (1) the data acquisition module; (2) the array processor; and (3) the supervisory computer and peripherals. The basic minimum system includes a one per rev signal for engine speed information, an array processor to calculate classification as well as overall system control, a disk system, the display monitor(s), the operator terminal, the printer, and the alarm/shutdown control. To include additional channels, another AP would be required for the next x number of channels. If faster sample rates are needed, less channels would be processed by the front-end processor and an additional AP would be incorporated to aid the minicomputer in calculating the category module probabilities. As mentioned in the classifier description Section 4.0, these category detection modules are independent and may be performed in parallel. A control interface bus, an array bus, and the host bus provide the necessary control, timing and data signals. Operator commands from a video terminal provide initialization and menu drive control of the SGHS. A printer provides hardcopy output. The magnetic tape stores the data for more detailed off-line analysis.

7.2 Hardware Components

The following subsections describe in detail the main components of the SGHS and their requirements.

7.2.1 Data Acquisition Module

As shown in Fig. 74, system inputs can be the real-time strain-gage signal, stored data from tape, or a calibration standard. The analog signal is sampled, buffered and output to the array bus. From the control bus, the signal conditioner receives the amplifier gain, the filter cutoff frequency, the sample rate, and the trigger. The control bus addresses each module and stores each of these signals in selected 16-bit registers. A crystal oscillator will provide a clock which will be divided down by an amount specified by the sample rate control signa' in order to generate the sample rate for the A/D. A maximum sample rate

of 10240 Hz over 0.8 sec, would require a buffer size of 8k (10240 samples/sec x 0.8 sec). The data output from each FIFO buffer will be controlled by the array interface via handshake signals (Full, Half Full, Clear, Ready, etc.). Data acquisition may be initiated with the trigger signal.

7.2.2 Array Processor

The array processor will perform the preprocessing front-end calculations. It will acquire the buffered data from x number of channels, scale it, and calculate the global features, i.e., stress, histogram, and FFT (x = 15 to 20 depending on the particular AP). It will then output approximately 75 values from each channel to the supervisory computer. The software program will be assembled and compiled by the host. Using the array interface, the AP will address and read the data from each of the channels. Using a sample rate of 1024 Hz, K of data will be acquired over an 0.8-sec time block. The AP must input data, calculate features, and output data all within 0.8 sec. Sufficient memory is needed for storing the buffered data in addition to storing and executing the processing software. Program facility will depend on the particular AP selected. Numerical accuracy will be minimized by its floating point capability. The final output features will be DMAed to the supervisory computer for further processing.

7.2.3 Supervisory Computer

The supervisory computer will operate in parallel to the array processor. It will be used for overall SGHS control and management in addition to performing the final strain gage classification (refer to software specifications Section 6.0 for more details). The necessary software programs will be developed for the computer using both assembly and high level languages (i.e., ANSI FORTRAN 77). Operator commands will be used to issue the control signals to the data acquisition modules and to output data to the printer for hard copy records. The central processor's 32 bit architecture will feature memory management, a bootstrap loader, and standard instructions for floating and fixed point arithmetic. The computer will also include a system terminal as well as several operator terminals. The operating system will provide for the concurrent execution of multiuser time-sharing, batch and real-time use. The computer will be able to handle interrupts and DMA transfers.

7.2.4 Disk

The data disk will be used to store particular compressor information. It will also be used for program storage and development.

7.2.5 Printer

The printer will be used to provide hardcopy records of information from the supervisory computer. Its capabilities will include the following: full line buffering, vertical and horizontal adjustment and upper and lower case character sets. Data will be transferred via an RS-232 or a 16 bit parallel interface or an equivalent.

7.2.6 Display

Data processed on-line will be displayed on the visual monitors for user selected combinations of stages or strain gages. The user may choose to display specific global features or the output Q's from the category module probability calculation, the event probability calculation or the final decision calculation.

7.2.7 Magnetic Tape

The magnetic tape will record the realtime strain gage signals and the one-per-rev signal to be used for off-line analysis. Due to problems/limitations in calibration, drift, and bandwidth associated with analog tape, a digital tape would be used instead to acquire data for off-line analysis. Three tapes would be needed to store data for all 100 strain gages. At a maximum sample rate of 10240 Hz, one digital tape would acquire 2 byte data words from 38 channels ((6250 bytes/in. x 125 in./sec)/20480 bytes/sec/channel). With a tape storage capacity of 145MB, 3 minutes of data would be written (145MB/(781KB/sec x 60 sec)). As shown in Fig. 73, the user may instead select to store the calculated global features. Channel synchronization, encoding, and storage selection would be controlled by a microprocessor (tape controller).

7.2.8 Safety Monitor

The safety monitor uses the calculated global features as well as continuously acquired run time information from the compressor in order to detect any unstable mechanical and aeromechanical condition and to provide evasive action.

7.2.9 Interfaces

Two buses (control and array) are used for interfacing within the computer hardware configuration. Figures 75 and 76 illustrate a conceptual interface configuration with those control signals needed to communicate with a FIFO.

As shown in Fig. 75, the array bus interface is used to transfer data from the data acquisition modules to the array processor. Five bits from the interface will selectively address up to 32 channels; the card slot for each module

will have a hardwired address. The FIFO Full and FIFO Half Full signals from the addressed module's FIFO to the interface indicate the FIFO's storage status. In order to input data from the FIFO, the interface first outputs a Read signal. Upon receiving a Ready signal from the FIFO, data will be input to the interface. Each module will output the three status signals (FIFO Full, FIFO Half Full, and FIFO Ready) to the array processor; thus, a maximum of 3 x signals are required where x is the number of channels processed by the selected AP.

The control bus interface, as shown in Fig. 76, transfers signals between the supervisory computer and the data acquisition modules. The computer specifies the amplifier gain, the filter cut-off frequency, and the sample rate. Using five bits to first address one of 32 modules (card slots), the interface then outputs a two-bit select code to enable the particular register receiving the control data. Once selected, 16 bits of control data are clocked into the register.

7.3 Array Processor Survey

As mentioned earlier, a survey of array processors was conducted in order to select an AP which would best fit the Strain-Gage Classifier application. Key issues were program and data memory, processing capability, ease of programming, cost, I/O capability, and finally, the throughput time for the typical case of one channel acquiring 4K of data with a sample rate of 5120 Hz. The Zip 3232 by Mercury best meets the specifications described above. Using the typical case, it is capable of processing 20 channels; thus five units would be needed for all 100 gages. This choice, however, is subject to change with the introduction of new products on the market.

8.0 CONCLUSIONS AND RECOMMENDATIONS

In this strain-gage signal interpretation program, a systematic study was made in order to define the hardware/software configurations of an expert system capable of monitoring and interpreting strain gage signals from jet engine compressor stages and immediately taking necessary evasive actions to ensure rig safety.

The expert system was designed to simulate closely the thinking process of experienced aeromechanical test engineers. To accomplish this objective, a comprehensive strain-gage data bank was first generated that contains all major categories of aeromechanical phenomena and noise signals from fan and compressor stages of various engines. The strain-gage data were analyzed in the time domain as well as the frequency domain so that significant signal features could be identified for various types of aeromechanic phenomena and noise. These individual signal features were combined with spatial (interblade and interstage), temporal and other syntactic features to form a complete feature set for each aeromechanical phenomenon or noise type.

The feature sets of all strain gages were then used in a three level classifier system to determine the probability values of each possible aeromechanical phenomenon and noise type. The first level of classification uses only the individual strain-gage features to determine the category probability for each phenomena and noise type. The second level of classification utilizes the spatial (interblade and interstage) features to refine the category pseudo-probability values and yield the event probability values. The third level of classification combines the temporal features with the event probability values to yield the final probabilities based on which decisions are made on the type of actions to be taken to ensure rig safety. Operator selective provisions were made to initiate early evasive actions for certain types of aeromechanical phenomena such as surge after the first or second level of classification if required. The modular structure of the three level classifier allows easy expansion or reduction of the expert system components for system improvement or optimization.

The strain gage classifier is based on a novel degradation logic designed to allow continued training of the classifier. The degradation logic involves several degradation constants that need to be specified. The degradation constants have been selected in this development effort for all major aeromechanic phenomena. For noise, only logical choices were made because the difficulty in identifying the precise noise types for the noise signals compiled at the early stage of the program. However, the logical choices made for noise degradation constants are based on extensive information exchange between many aeromechanical test engineers and signal processing personnel and are

considered the most reliable baseline information upon which improvement can be made through further training of the classifier. It is felt that the noise degradation constants can be best selected using noise signals generated in the laboratory by producing the noise source, such as strain-gage grid separation, recorder circuit short, etc., so that uncertainty in the types of noise can be eliminated.

The baseline software/hardware system specifications have been defined to acquire strain gage data, calculate global features, then use these features to determine the predominant aeromechanical phenomena. Up to 100 strain-gage channels are to be incorporated into the system on a modular basis. A one-per-rev signal provides engine speed information. Each channel carries an analog signal to a data acquisition module. The signal is digitized and 4K of data corresponding to 0.8 sec. is buffered. An array processor calculates the stress, histogram, and FFT global features for 15 to 20 channels. The actual number of channels depends on the particular array processor selected. A supervisory minicomputer uses the global features from all channels to classify the aeromechanical phenomena and to take evasive action if necessary. The minicomputer operates in parallel with the array processor. The overall system is expected to produce real time displays within a one to two second update rate during online operation.

REFERENCES

1. Smalley, R. R.: Microprocessor-Based Multichannel Flutter Monitor Using Dynamic Strain-Gage Signals, NASA TMX-71884, also presented at National Instrumentation Symposium sponsored by the Instrument Society of America, San Diego, California, May 25-27, 1976.

2. Fowler, R. B.: Online Monitoring of Compressor Blade Stress: An Improved System, AEDC-TR-79-7, April 1979.

3. Harper, R. E. and F. M. Reichenbach: A Computer-Based System for Processing Dynamic Data, Instrument Society of America Transactions, Vol. 17, No. 1, 1978, pp. 57-64.

4. Proposal for Strain-Gage Signal Interpretation, UTRC P82-279, September 1982.

5. Greitzer, E. M.: Surge and Rotating Stall in Axial Flow Compressors, Pt. 1 and Pt. 2, Journal of Engineering for Power, April 1976, pp. 190-217.

TABLE 1 - VIBRATION CHARACTERISTICS

FEATURE	RES	FLT	SFV	VAN	ROT	SRG	RUB	NRV
Integral Order	Yes	NO	No	Yes	No	No	Yes	Yes
AMPLITUDE	9 CONSTANT IM = 0 to 10 P/RMS ≈ $\sqrt{2}$	7 CONSTANT IM = 0 to 10 P/RMS ≥ $\sqrt{2}$	9 RANDOM IM = 10 to 100		6 CONSTANT	9 Very large spikes within SRG pulse	7 Medium to large amplitude spikes	7 CONSTANT low level
PHASE	10 Fixed wrt casing	9 Rotates wrt casing 9 Fixed between blades	9 Random Phase		9 Rotates wrt casing	9 Random Phase	10 Leading spike fixed wrt casing	
FREQUENCY	9 Single frequency 3 Multimodal	9 Single Frequency, 1 First flex mode 9 First torsional mode 1 Second flex	2 Several blade modes 8 First flex mode present		7 Sub EO for one stall cell (.5% to 60% EO) 8 First blade modes 1 Higher blade modes	8 Broad content 8 Heavy first flex mode 8 Very low pulse repetition frequency looks like a DC shift (if DC coup.)	8 1E Rub component 9 First flex mode 1 Higher modes	9 1E Typical
SIGNATURE	9 Sinusoidal 9 Very regular modulation pattern (if present) 5 Nth [illegible] of excitation causes every Nth RES peak to be larger	8 Sinusoidal 9 Nonregular modulation pattern wrt casing (if present) 9 Rapid rise to a stabilized amp	9 Randomly modulated sinusoid	10 VAN problem is detuned by effects on other stages, usually downstream	9 Multiple cells present 2 Single cell observable on strain gage 9 Cell travels at half speed, (15% to 65% EO)	10 Very fast rise time 9 SRG width from 0.05 to 0.5 sec contains 10 to 100 mode oscillations 6 SRG pulse repeats up to 12/sec 9 Flow reversal oscillations 10 Observable on all probes in comp.	8 Impact followed by decay at natural mode 6 Low impacts are often masked by other vibrations 7 Large number of outliers	Any EO stimulus that is not constant 4 1E Modal pattern 3 Beat Phenomenon 7 Like RES only small amplitude
INTERBLADE	9 Circumferential dovetail ⇒ single blade RES Axial dovetail 7 ⇒ Stage RES 10 ⇒ Fixed between blades and stationary in space	8 All blades involved 7 Amplitude varies 10 to 1 among blades 8 Same frequency 9 θ rotates in space	8 Large amplitude and phase variation between blades 5 Different first mode frequencies between blades		See RES if ROT excites resonance	10 All blades involved	4 Not necessarily on all blades	7 All blades
INTERSTAGE	9 Single stage	9 Single stage	8 Front end stages of high compressor at low speeds due to high incidence angle	Effects First upstream and several downstream stages 8 A stage is excited when EO=blade mode	7 Multistage but at very different amplitudes, barely perceptible on adjacent stages	10 All stages involved 5 Max stresses in middle stages	9 Single stage	7 Single stage
CONFUSED-WITH OR LOOKS-LIKE	1 FLT: when FLT is 10 use IM 2 ROT: ROT cell may excite RES	1 RES: when FLT is 10 use IM 3 ROT: when cell passing freq. is not 10 5 SFV: first flex SFV often called flutter	4 SRG:	7 Upstream obstructions, leftover tools, open blued holes, instrumentation probes 4 Low level RUB 5 Beat Phenomenon at 1 per rev	7 RES: But nonintegral order, remaining constant with speed	4 SFV:	8 Loose VAN ⇒ initial impact varies widely 5 Missing VAN ⇒ constant impact but less than RUB 3 Beat phenomenon when impacts are very low	4 RUB: low-level
OCCURS-WITH	10 Speed change 10 Stationary disturbance 2 ROT. Stall cells may excite RES 4 RUB. Sharp rub spikes may excite RES	3 At constant speed FLT can occur when pressure ratio is changed 4 Follows SFV 3 Precedes SRG	4 Precede SRG 5 VAN: Can cause SFV in a downstream stage 6 Precede FLT, SFV to FLT gives mode change from flex to torsional	8 RES: Unexpected RES on internal stage 3 SFV:	7 Precedes and/or follows SRG	8 Precedes and/or follows ROT 7 Follows SFV	4 VAN: If misrigged VAN actually contacts the blade	5 VAN problem
SPEED DEPENDENCE OR MISC	10 RES peak amplitude and peak dθ/dt occurs when EO= blade mode 7 RES BW=TOL=5% F_r	7 Stall flutter high load, $V/b\omega_t > 1$ 7 Choke flutter low loading 9 Supersonic unstalled flutter	8 Front end SFV Occurs at lower speeds, ≤ 80% speed 7 Back end SFV is large at high speed (ramp effect)	8 As speed changes different stages will be excited	8 ROT near hub seen best on vanes 8 ROT near casing seen best on blades	9 Strong SRG seldom experienced below 70% speed	8 More pronounced during transients or during break-in	

VIBRATION CHARACTERISTIC KEY

		Occasionally				Often			Always
1	2	3	4	5	6	7	8	9	10
Rarely				50/50				Usually	

DEFINITIONS

IM = (Max Stress - Min Stress)/Max Stress
P/RMS = Peak Stress/RMS Stress
wrt = with respect to
θ = Phase Angle

DEFINITIONS (Cont'd)

BW = Frequency Bandwidth
F_r = Resonance Frequency
EO = Engine Order; rotational frequency
IO = Integral Order; integral multiple of EO
$V/b\omega_t$ = Reduced Velocity; V = inlet velocity
b = half chord
ω_t = torsional frequency

TABLE 2

NOISE CHARACTERISTICS

FEATURE	LINE NOISE	SLIP RING	TELEMETRY	OPEN CIRCUIT	SHORT CIRCUIT	SUPERSENSITIVITY	INTERMITTENT NOISE
Integral Order	No		Yes	No			
Amplitude	constant		constant	large saturation	sharp drop of signal to zero	large	random
Frequency	60 Hz and/or higher harmonics	discrete one-per-rev or continuous	two-per-rev				
Signature	periodic if line noise dominates	initially one-per-rev; eventually turn random grassy look; one sided		one-sided waveform			nonstationary random bursts of high intensity signals
Interblade		occurs for blades linked to the same slip ring				usually one blade	
Interstage							
Confused-With or Looks-Like			resonance	loss of blade		resonance or flutter	
Occurs With				often after surge	often after surge		
Speed Dependence or Misc		Signal deteriorates as time progresses	exist for wide speed range	caused by strain gage grid separation or disconnection of electronic instruments, etc; amplitude stays constant as speed varies	caused by strain gage insulation breakdown or electronic instrument circuit short	possibly caused by localized necking down of strain gage grid	caused by electrical or mechanical disturbances

TABLE 3

PROCESSING LIMITATIONS DUE TO SAMPLING RATE
(Block Size = 4096)

Rate	Sample Time T	Frequency Resolution DF	f_{High}	Max EO Based on 12000 RPM
1024 Hz	4.0 secs	0.25 Hz	512 Hz	2
5720 Hz	0.8 secs	1.25 Hz	2560 Hz	12
25600 Hz	0.16 secs	6.25 Hz	12800 Hz	60

TABLE 4

TAPE DATA BLOCK PARAMETERS

1	NCH - number of channels			
2	TSM - tape search mode	0-manual	1-auto	
3	TBH - tape search start hour			
4	TBM - tape search start minute			
5	TBS - tape search start second			
6	TFH - tape search finish hour			
7	TFM - tape search finish minute			
8	TFS - tape search finish second			
9	PKS - number of peaks			
10	PK1 - peak number			
11	PK2 - peak number			
12	PK3 - peak number			
13	PK4 - peak number			
14	BKI - acquisition block interval			
15	DIG - digitizing rate			
16	BSZ - block size			
17	TCH - tape characteristics	0-old	1-new	
18	NBR - number blocks requested			
19	NBA - number blocks acquired per gauge			
20	AMD - acquisition mode	0-time	1-speed	
21	ERR - acquisition status	1-error	1-no error	
22	SRC - data source	0-simulator	1-A/D's	
23	SIM - simulator mode	0-hold	2-decrement	4-increment
24	SED - simulator seed			
25	CLK - clocking source 0-N2 2-N1 4-interval			
26	TTH - number of tachometer teeth 1, 4, 46, or 60			
27	GRT - gear ratio			
29	BV1 - RPM band value 1			
30	BV2 - RPM band value 2			
31	TDS - tape recorder day started			
32	TDF - tape recorder day finished			
33	AQT - acquisition type 1-calibration 2-data			
34	EDB - RPM error band			
35	SSL - RPM initial value source	0-manual	1-auto	
36	SVL - RPM initial value			

TABLE 5

GLOBAL FEATURE EXTRACTION OPTIONS

STRESS

1	SKIP	1 = Do not compute stress features
2	NBIN	Number of subintervals in data block
3	MAXBIN	Maximum subintervals; currently 8

HISTOGRAM

1	SKIP	1 = Do not compute Histogram features
2	NBINS	Number of stress bins on histogram abscissa
3	MODE	0 = Use VMIN/VMAX for stress limits 1 = Find and use actual min and max stress
4	VMIN	Minimum stress value on histogram abscissa
5	VMAX	Maximum stress value on histogram abscissa

FFT

1	SKIP	1 = Do not compute FFT features
2	NBEG	Beginning point in data block to be transformed
3	NEND	Ending point in data block to be transformed
4	NDC	1 = compute and subtract DC value before FFT
5	NFFT	Size of FFT, truncate or zero-fill data accordingly
6	NWND	1 = Use Hamming window, 2 = use Hanning window
7	NBINS	Number of Bins for Histogram of Power spectrum
8	MXPK	Number of spectral Peaks to be found
9	MAXPK	Maximum number of peaks; currently 10
10	THRPK	Peak threshold factor, 0 = use threshold at address (1,2,2,1,3,2)
11	T[illegible]L	Lower BW threshold factor, 0 = use threshold at address (1,2,2,1,3,3)
12	THRBWU	Upper BW threshold factor, 0 = use threshold at address (1,2,2,1,3,4)
13	NLEVEL	Percentile of histogram to define stress noise level
14	SORT	0 = Store peaks by frequency, 1 = store by amplitude, 2 = store by area
15	IOTOL	Integral order tolerance in multiples of DF (frequency resolution)

TABLE 6A

GLOBAL FEATURES (THRESHOLD AND STRESS)

THRESHOLD

1	ITH	Point at which threshold is exceeded
2	V(ITH)	Stress value at ITH
3	SFLAG	Scale flag from run options
4	SCALE	Scale value applied to data
5	DCFLAG	DC flag from run options
6	DC	DC value subtracted from data

STRESS

1	STRP	Peak stress value
2	NTRP	Index of STRP
3	STR2	Second highest stress value
4	NTR2	Index of STR2
5	STR3	Third highest stress value
6	NTR3	Index of STR3
7	STRA	Average stress
8	STRR	RMS Stress
9	STRP/STRR	Peak stress/RMS stress ratio
10	POWER	Total stress energy (sum of squares)
11	VARP	Variation of peak stress in subintervals: (max-min)/max
12	VARA	Variation of average stress in subintervals
13	VARR	Variation of RMS stress in subintervals
14	VARS	Variation of peak/RMS ratio in subintervals

STRESS SUBINTERVALS (For each of up to eight subintervals)

1	PEAK	Peak stress in subinterval
2	AVG	Average stress in subinterval
3	RMS	RMS stress in subinterval
4	PEAK/RMS	Peak/RMS ratio in subinterval

TABLE 6B

GLOBAL FEATURES (HISTOGRAM)

1	NBIN	Number of Histogram Bins
2	MNMX	Mode from run options
3	VMIN	Actual value of stress used for abscissa minimum
4	VMAX	Actual value of stress used for abscissa maximum
5	MN	Mean stress
6	MED	Median stress
7	MODE	Mode stress
8	VAR	Variance of stress
9	SDV	Standard deviation of stress
10	MC2	Second central moment
11	MC3	Third central moment
12	MC4	Fourth central moment
13	SKW	Skewness
14	KUR	Kurtosis
15	M99	0.99 Percentile stress value
16	M98	0.98 Percentile stress value
17	M95	0.95 Percentile stress value
18	M90	0.90 Percentile stress value
19	M80	0.80 Percentile stress value

TABLE 6C

GLOBAL FEATURES (FFT)

POWER

1	TPOWER	Total stress energy from FFT sum of squares
2	VNOIZ	Stress noise power level from PS Histogram
3	PLEVEL	Percentile of PS Histogram for determining UNOIZ
4	AINCR	Stress power increment per PS Histogram BIN
5	THRPK	Computed threshold for determining PS peaks
6	THRBWL	Computed threshold for determining lower BW of peaks
7	THRBWU	Computed threshold for determining upper BW of peaks
8	RPS	Computed rotational frequency: RPM/60
9	NMODE	Number of blade modes defined and used

PEAK (For each Peak of PS exceeding THRPK)

1	MPKS	Number of peaks found
2	NPK	Index of peak
3	FREQ	Frequency of peak (Hz)
4	VPK	Stress value of peak (PSI*PSI)
5	VPHS	Phase of peak (DEG)
6	NWL	Lower bandwidth (samples)
7	NWU	Upper bandwidth (samples)
8	APK	Area (energy) of peak; sum of squares within NWL
9	EPK	Ratio of energy in peak to total energy; APK/TPOWER
10	RAPK	Ratio of energy in this peak to energy in all MPKS peaks
11	RACC	Cumulative energy in this peak and preceding peaks
12	EO	Engine order; FREQ/RPS
13	FERR	Error from nearest integral order: -0.5 to 0.5
14	IO	Integral order indicator; 0 = nonintegral order
15	IMODE	Closest blade mode number; -1 = no modes specified
16	FMODE	Modal frequency of IMODE
17	FMERR	Normalized modal error in units of modal bandwidths
18	MTYPE	Mode type; 0 = flex, 1 = torsional
19	SPK	Equivalent sinusoidal stress amplitude for this peak

TABLE 7

DEGRADATION CONSTANTS

		RES	FLT	SFV	VAN	ROT	SRG	RUB
F1	W	5	9	0	5	9	0	0
	FN	1	1		1	5		
MPKS	D	7	3		7	5		
	EXP	1	2		1	1		
	MODE	0	1		0	0		
F2	W	10	0	0	10	0	0	0
	FN	0			0			
FERR	D	.5			.5			
	EXP	1			1			
	MODE	0			0			
F3	W	10	0	0	10	0	0	0
	FN	0			0			
FERR2	D	.5			.5			
	EXP	1			1			
	MODE	0			0			
F4	W	10	0	0	10	0	0	0
	FN	0			0			
FERR3	D	.5			.5			
	EXP	1			1			
	MODE	0			0			
F5	W	5	0	0	5	0	0	0
	FN	.6			.6			
RAPK	D	.4			.4			
	EXP	1			1			
	MODE	-1			-1			
F6	W	6	0	6	6	6	0	0
	FN	.6		.5	.6	.4		
EPK	D	.4		.2	.4	.2		
	EXP	1		1	1	1		
	MODE	-1		-1	-1	-1		
F7	W	8	0	8	8	8	0	0
	FN	5		16	5	13		
BWL	D	10		2	10	5		
	EXP	1		1	1	1		
	MODE	1		-1	1	1		

TABLE 7 (Cont'd)

		RES	FLT	SFV	VAN	ROT	SRG	RUB
F8	W	0	0	0	0	0	0	10
	FN							0
EOERR	D							.5
	EXP							1
	MODE							0
F9	W	0	0	0	0	0	0	10
	FN							0
FIERR	D							2
	EXP							1
	MODE							0
F10	W	6	0	8	6	8	8	0
VARR	FN	.1		.5	.1	.8	.7	
	D	.2		.3	.2	1.	1	
	EXP	1		1	1	1	1	
	MODE	1		0	1	-1	-1	
F11	W	8	8	8	8	8	8	8
KUR	FN	2.5	2.5	2.5	2.5	5.	8	3
	D	.5	.5	.5	.5	1.	1.	1
	EXP	1	1	1	1	1	1.	1
	MODE	1	1	0	1	-1	-1	-1
F12	W	0	0	0	0	0	0	0
	FN							
SKW	D							
	EXP							
	MODE							
F13	W	9	9	0	9	0	0	9
	FN	1	1		1			1
NUTHR	D	1	1		1			1
	EXP	1	1		1			1
	MODE	0	0		0			0
F14	W	6	9	0	6	6	0	0
	FN	1	1		1	1		
IALL	D	1	1		1	1		
	EXP	1	1		1	1		
	MODE	0	0		0	0		

TABLE 7 (Cont'd)

		RES	FLT	SFV	VAN	ROT	SRG	RUB
F15	W	0	9	0	0	6	0	0
	FN		1			1		
IFREQ	D		1			1		
	EXP		1			1		
	MODE		0			0		
F16	W	0	0	0	0	10	0	0
	FN					1		
IADJ	D					.5		
	EXP					1		
	MODE					0		
F17	W	0	0	0	0	0	10	0
	FN						1	
ITOTUN	D						.2	
	EXP						1	
	MODE						0	
F18	W	0	0	8	0	0	0	0
	FN			1				
I_{BACK}^{FRONT}	D			1				
	EXP			1				
	MODE			0				
F19	W	0	0	5	0	0	5	0
	FN			1			1	
IMODE	D			2			2	
	EXP			1			1	
	MODE			0			0	
F20	W	0	0	5	0	0	5	0
	FN			0			0	
MTYPE	D			1			1	
	EXP			1			1	
	MODE			0			0	

TABLE 8

CALCULATED PROBABILITIES

RESONANCE

CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	QRUB
1	0.91	0.63	0.00	0.91	0.26	0.00	0.22
2	0.85	0.64	0.30	0.85	0.17	0.00	0.16
3	0.97	0.64	0.00	0.97	0.22	0.00	0.17
4	0.85	0.55	0.00	0.85	0.30	0.00	0.27
5	0.97	0.64	0.00	0.97	0.19	0.00	0.12
6	0.96	0.64	0.00	0.96	0.21	0.00	0.15

FLUTTER

CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	QRUB
1	0.58	1.00	0.07	0.58	0.13	0.00	0.18
2	0.19	0.69	0.00	0.19	0.30	0.00	0.00
3	0.46	0.78	0.00	0.46	0.17	0.00	0.29
4	0.57	0.36	0.00	0.57	0.20	0.00	0.26
5	0.57	0.51	0.00	0.57	0.27	0.00	0.29
6	0.73	0.91	0.10	0.73	0.16	0.00	0.10

SFV

CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	QRUB
1	0.61	0.70	0.87	0.61	0.00	0.00	0.31
2	0.44	0.41	0.70	0.44	0.00	0.00	0.46
3	0.41	0.07	0.75	0.41	0.00	0.00	0.44
4	0.58	0.70	0.80	0.58	0.00	0.00	0.27
5	0.48	0.47	0.79	0.48	0.10	0.00	0.42
6	0.64	0.15	0.72	0.64	0.06	0.00	0.40

MRV

CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	QRUB
1	0.74	0.70	0.33	0.74	0.02	0.00	0.12
2	0.72	0.77	0.36	0.72	0.00	0.00	0.07
3	0.80	0.80	0.29	0.80	0.00	0.00	0.05
4	0.90	0.43	0.00	0.90	0.05	0.00	0.06
5	0.83	0.43	0.00	0.83	0.10	0.00	0.12
6	0.80	0.43	0.00	0.80	0.07	0.00	0.03

ROT

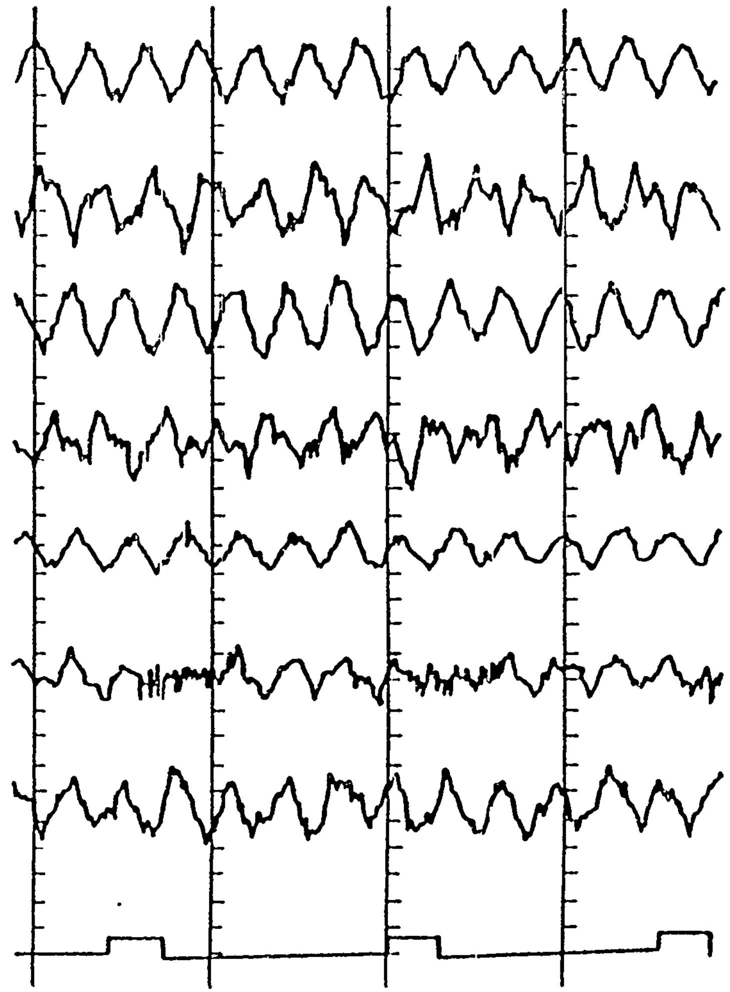
CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	QRUB
1	0.00	0.00	0.00	0.00	1.00	0.00	0.32
2	0.00	0.00	0.00	0.00	1.00	0.00	0.32
3	0.00	0.00	0.00	0.00	1.00	0.00	0.32
4	0.00	0.00	0.00	0.00	0.84	0.00	0.32
5	0.00	0.00	0.00	0.00	0.02	0.00	0.32
6	0.00	0.06	0.00	0.00	0.33	0.00	0.32
7	0.00	0.00	0.00	0.00	0.39	0.00	0.32
8	0.00	0.00	0.00	0.00	0.41	0.00	0.32
9	0.00	0.00	0.00	0.00	0.31	0.00	0.32

SRG

CASE ID	QRES	QFLT	QSFV	QVAN	QROT	QSRG	ORUB
1	0.00	0.00	0.00	0.00	0.09	1.00	0.00
2	0.00	0.00	0.00	0.00	0.09	1.00	0.00
3	0.00	0.00	0.00	0.00	0.00	1.00	0.00
4	0.00	0.00	0.00	0.00	0.20	1.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.98	0.00

BLADE CIRCUMFERENTIAL POSITION DEGREES	GAGE LOCATION	MEASURED PHASE
11	RLE	0
45	ASMT	300
45	RLE	150
34	ASMT	?
34	RLE	120
0	ASMT	90
11	ASMT	170

SPEED 1/REVOLUTION



82-9-51-1

Figure 1. Blade Flutter Strain-Gage Signals (Unfiltered)

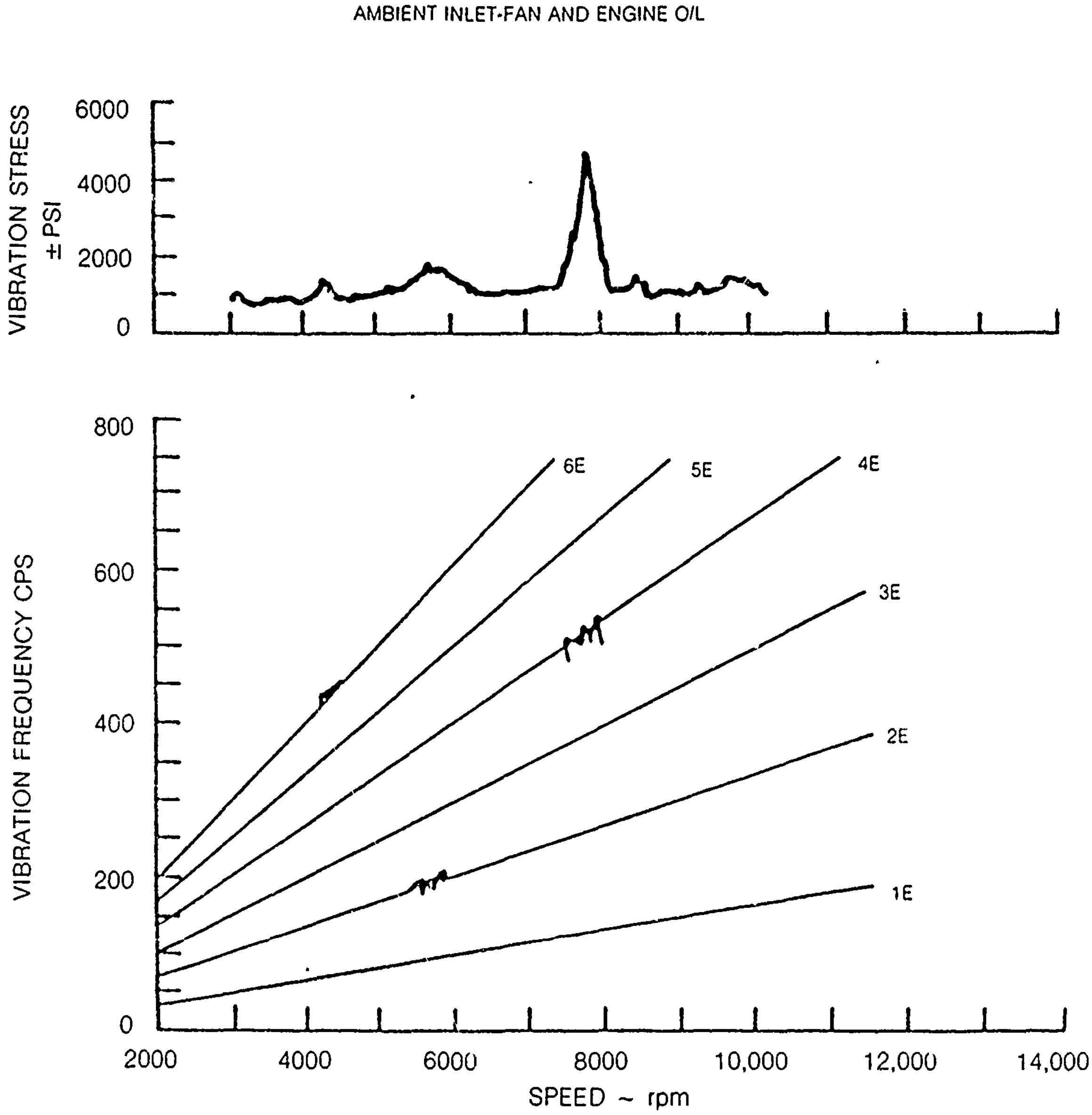


Figure 2. Resonant Characteristics of Third-Stage Fan Blade With Clean Inlet

82-9-51-3

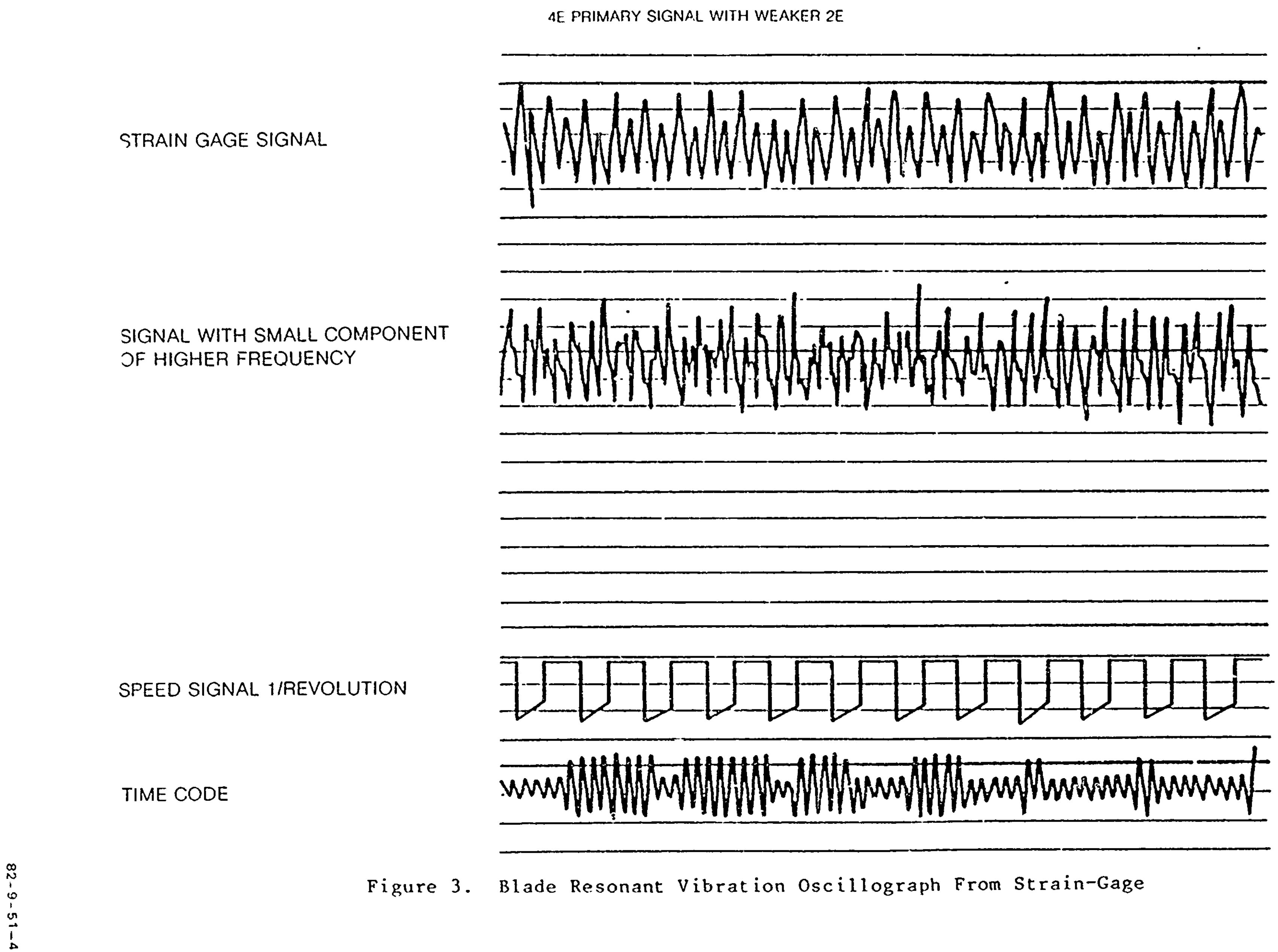


Figure 3. Blade Resonant Vibration Oscillograph From Strain-Gage

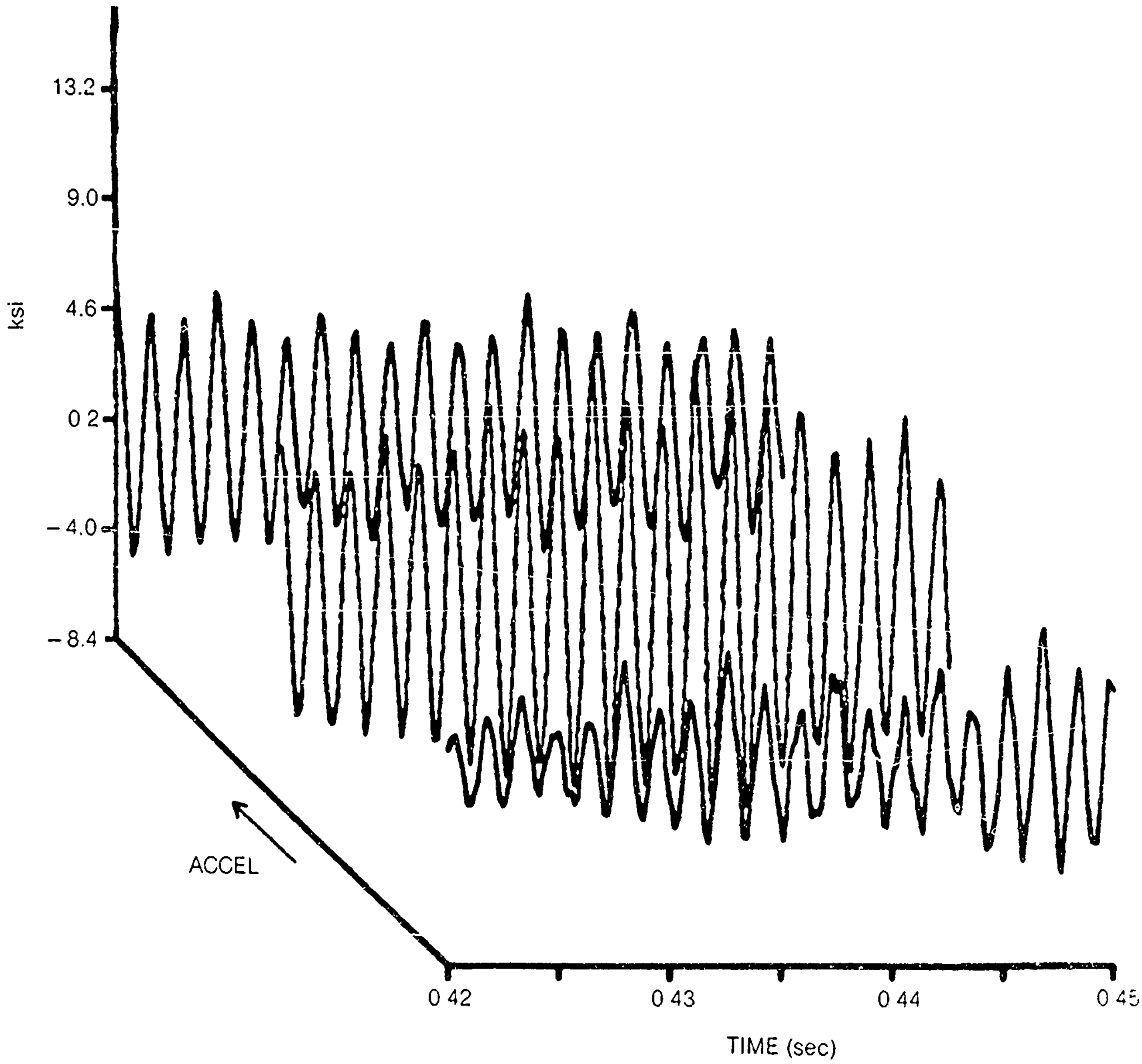


Figure 4. Waveforms of Separated Flow Vibration

85-3-55-16

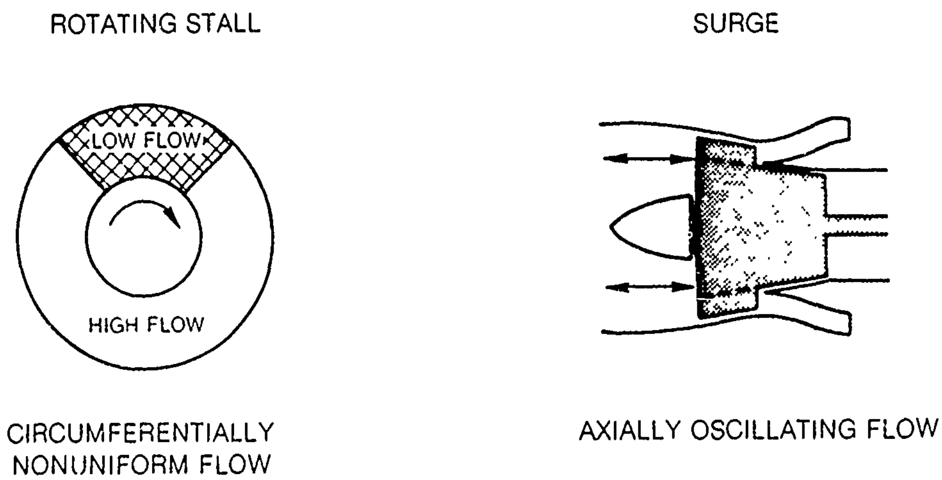


Figure 5. Possible Modes of Instability on the Stall Line

82-9-51-6

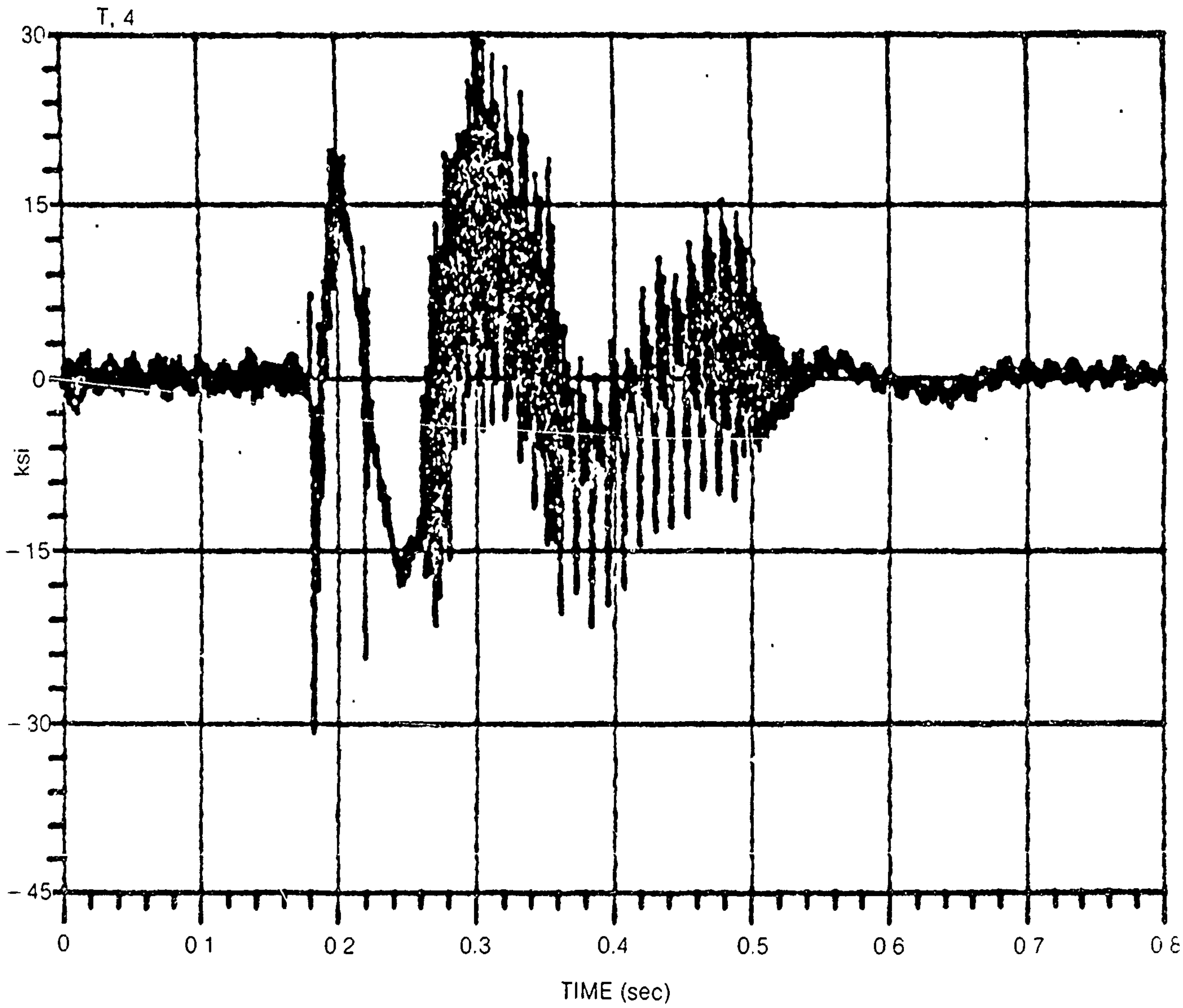


Figure 6. Waveform of Surge and Rotating Stall

85-3-55-17

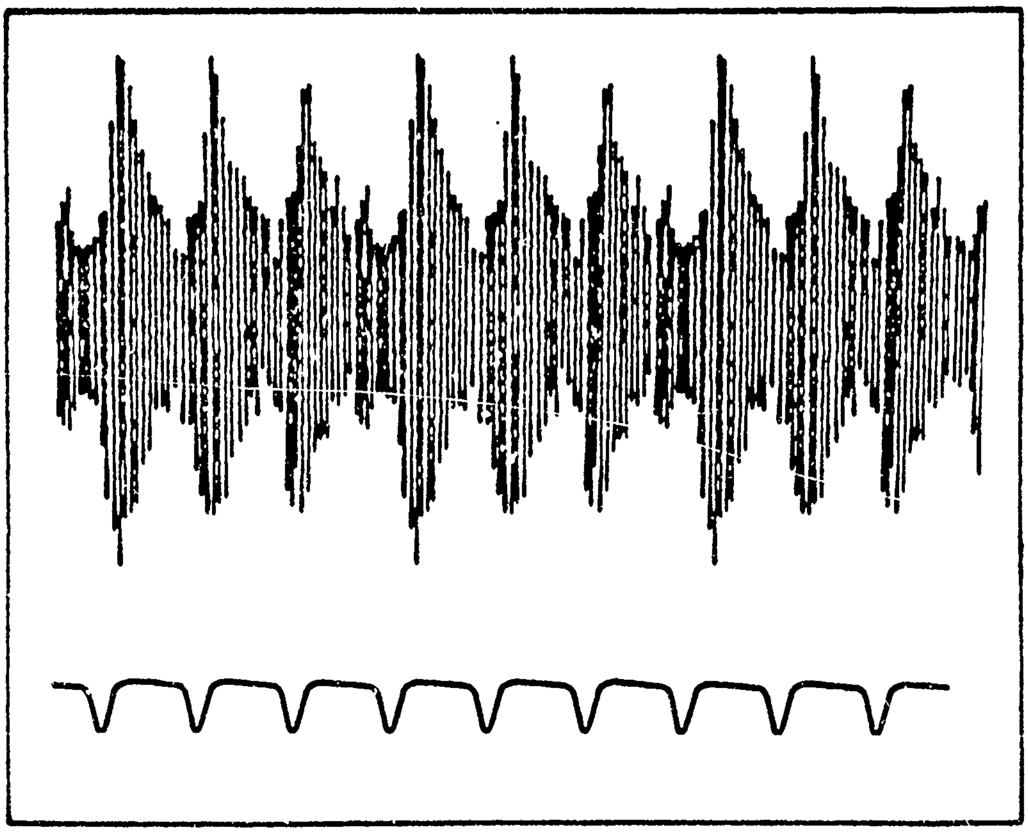


Figure 7. Typical Tip-Rub Signal

85-3-55-15

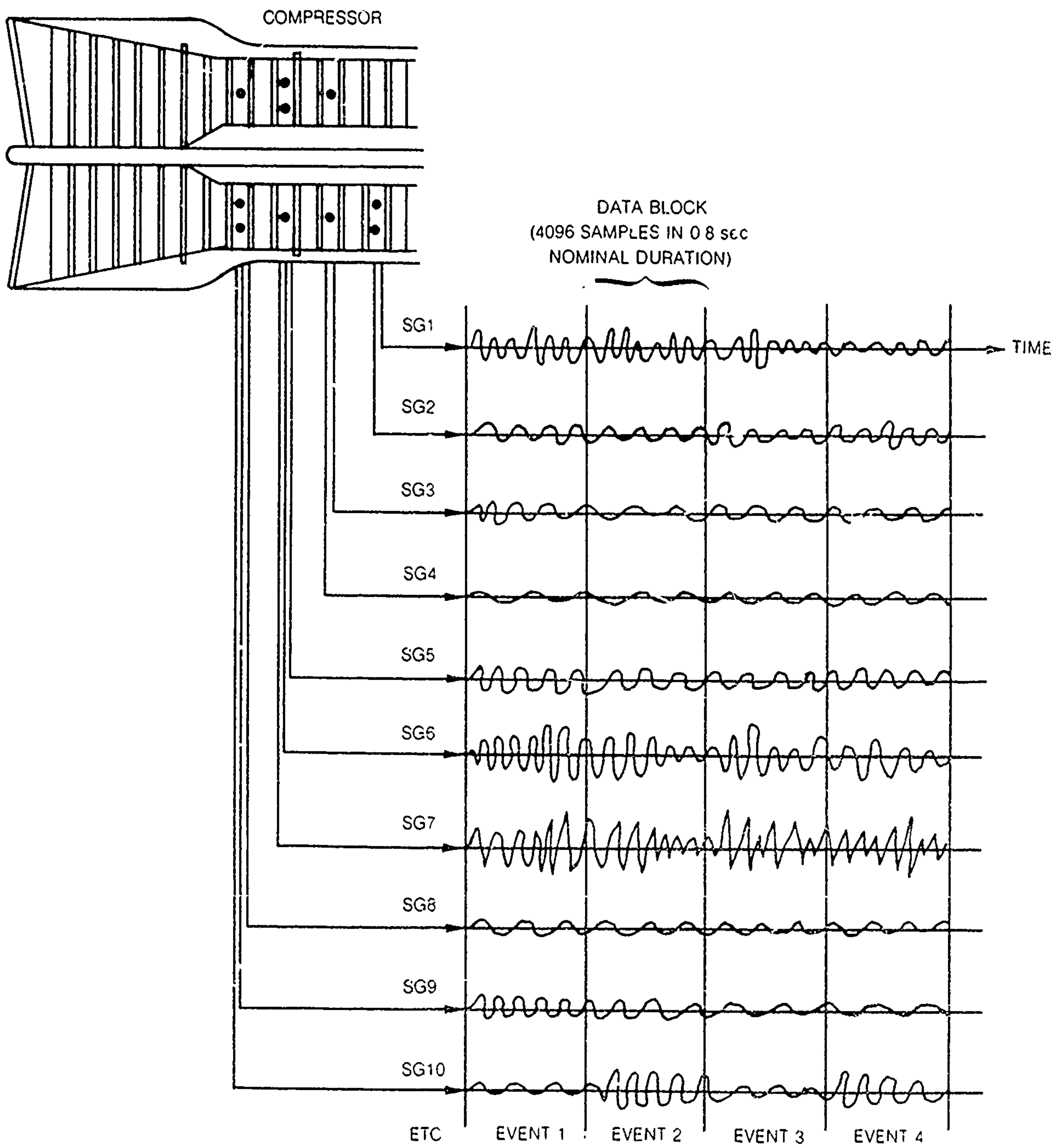
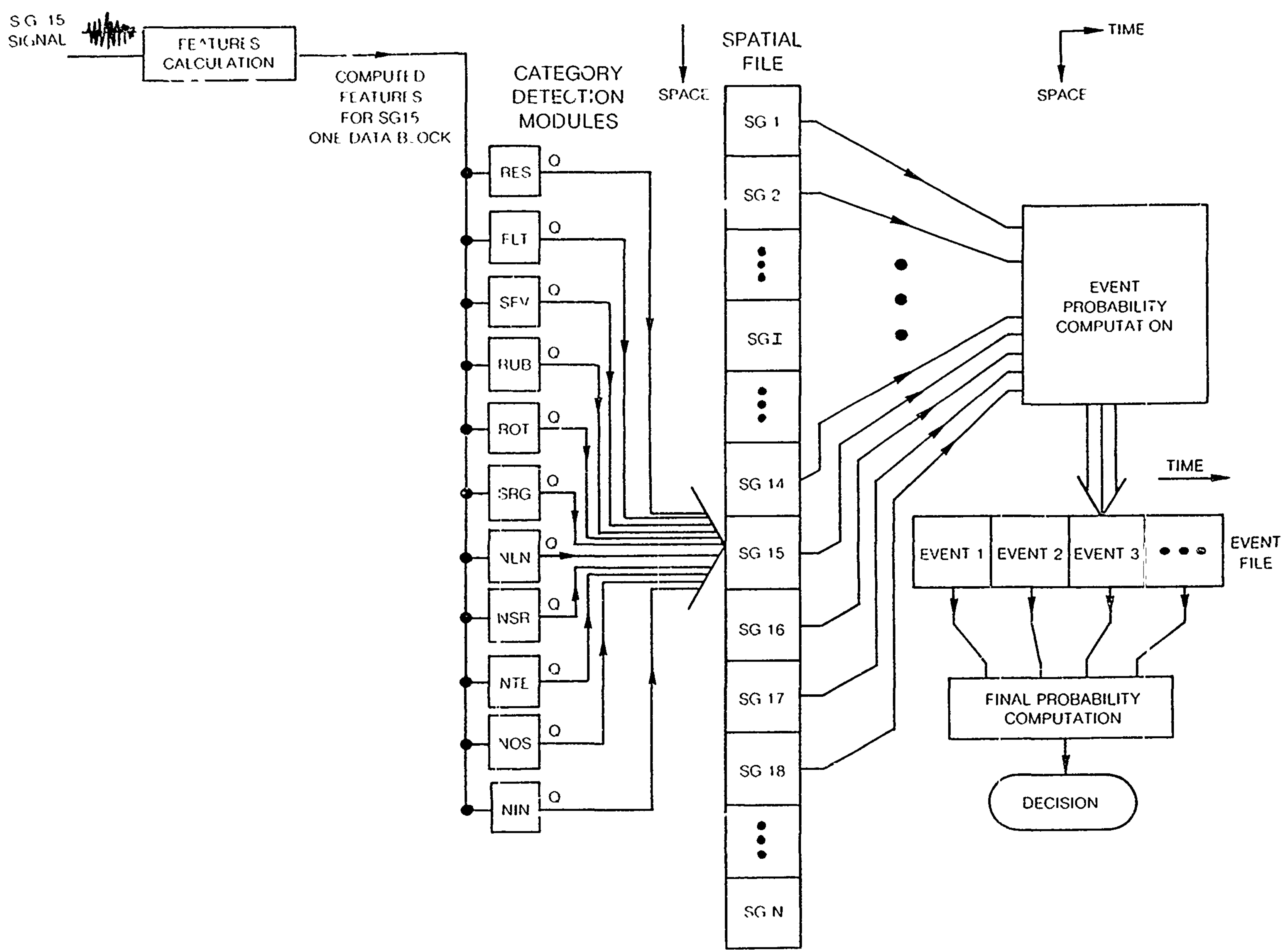


Figure 8. Data Acquisition Format

84-5-16-1



84-10-36-1

Figure 9. Classifier Data Flow

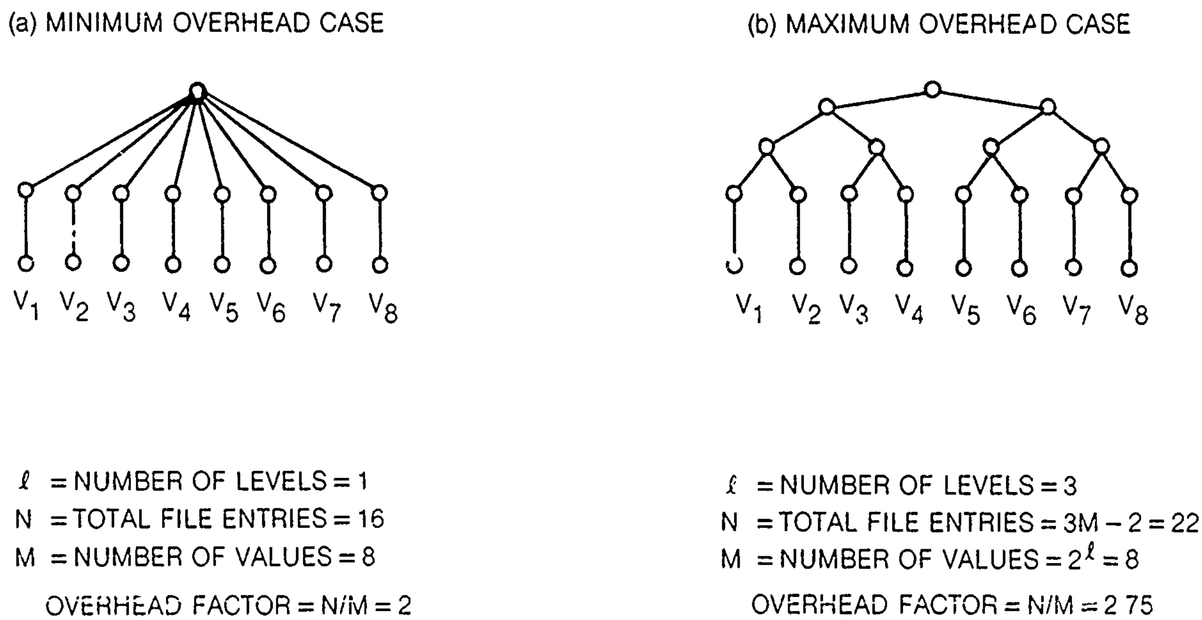
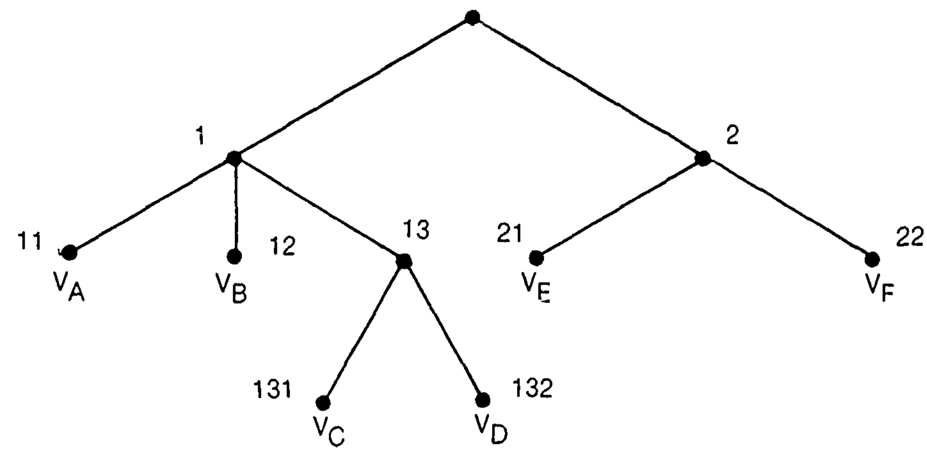


Figure 10. Basic Tree Structures

84-5-16- 3



FILE ADDRESS	TREE ADDRESS	CONTENTS
1	X	3
2	X	12
3	X	6
4	X	7
5	X	8
6	1, 1, 0	V_A
7	1, 2, 0	V_B
8	X	10
9	X	11
10	1, 3, 1, 0	V_C
11	1, 3, 2, 0	V_D
12	X	14
13	X	15
14	2, 1, 0	V_E
15	2, 2, 0	V_F

Figure 11. Tree Address Example

84-5-16-4

```
ZWICKE*DATA(1).AASGEEE(1)
PUT
N
1,2,1,1,1,0,0,0
3
3.,70749.,14000.
1,2,1,4,1,0,0,0
5
20.,0.,0.,0.,1.
1,2,2,1,1,1,0,0
2
1.,0.
1,2,2,1,2,1,0,0
1
32.
1,2,2,1,2,2,0,0
1
0.
1,2,2,1,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,2,1,1,0,0
2
0.,0.
1,2,2,2,2,1,0,0
1
26.
1,2,2,2,2,2,0,0
1
0.
1,2,2,2,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,3,1,1,0,0
2
1.,0.
1,2,2,3,2,1,0,0
1
44.
1,2,2,3,2,2,0,0
1
0.
1,2,2,3,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,4,1,1,0,0
2
0.,0.
1,2,2,4,2,1,0,0
1
50.
1,2,2,4,2,2,0,0
1
0.
1,2,2,4,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,5,1,1,0,0
2
1.,0.
1,2,2,5,2,1,0,0
1
50.
1,2,2,5,2,2,0,0
1
0.
1,2,2,5,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,6,1,1,0,0
2
0.,0.
1,2,2,6,2,1,0,0
1
60.
1,2,2,6,2,2,0,0
1
0.
1,2,2,6,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,7,1,1,0,0
2
1.,0.
1,2,2,7,2,1,0,0
1
52.
1,2,2,7,2,2,0,0
1
0.
1,2,2,7,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,8,1,1,0,0
2
0.,0.
1,2,2,8,2,1,0,0
1
66.
1,2,2,8,2,2,0,0
1
0.
1,2,2,8,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,9,1,1,0,0
2
1.,0.
1,2,2,9,2,1,0,0
1
60.
1,2,2,9,2,2,0,0
1
0.
1,2,2,9,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,10,1,1,0,0
2
0.,0.
1,2,2,10,2,1,0,0
1
62.
1,2,2,10,2,2,0,0
1
0.
1,2,2,10,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,11,1,1,0,0
2
1.,0.
1,2,2,11,2,1,0,0
1
64.
1,2,2,11,2,2,0,0
1
0.
1,2,2,11,3,1,0,0
5
4000.,32.,33.,34.,35.
1,2,2,12,1,1,0,0
2
0.,0.
```

Figure 12. Example of Compressor Information Block

84-5-16-45

```
144  1,2,2,12,2,1,0,0
145  1
146  56.
147  1,2,2,12,2,2,0,0
148  1
149  0.
150  1,2,2,12,3,1,0,0
151  5
152  4000.,32.,33.,34.,35.
153  1,2,2,13,1,1,0,0
154  2
155  1.,0.
156  1,2,2,13,2,1,0,0
157  1
158  72.
159  1,2,2,13,2,2,0,0
160  1
161  0.
162  1,2,2,13,3,1,0,0
163  5
164  4000.,32.,33.,34.,35.
165  1,2,2,14,1,1,0,0
166  2
167  0.,0.
168  1,2,2,14,2,1,0,0
169  1
170  64.
171  1,2,2,14,2,2,0,0
172  1
173  0.
174  1,2,2,14,3,1,0,0
175  5
176  4000.,32.,33.,34.,35.
177  1,2,2,15,1,1,0,0
178  2
179  1.,0.
180  1,2,2,15,2,1,0,0
181  1
182  64.
183  1,2,2,15,2,2,0,0
184  1
185  0.
186  1,2,2,15,3,1,0,0
187  5
188  4000.,32.,33.,34.,35.
189  1,2,2,16,1,1,0,0
190  2
191  0.,0.
192  1,2,2,16,2,1,0,0
193  1
194  70.
195  1,2,2,16,2,2,0,0
196  1
197  0.
198  1,2,2,16,3,1,0,0
199  5
200  4000.,32.,33.,34.,35.
201  1,2,2,17,1,1,0,0
202  2
203  1.,0.
204  1,2,2,17,2,1,0,0
205  1
206  72.
207  1,2,2,17,2,2,0,0
208  1
209  0.
210  1,2,2,17,3,1,0,0
211  5
212  4000.,32.,33.,34.,35.
213  1,2,2,18,1,1,0,0
214  2
215  0.,0.
216  1,2,2,18,2,1,0,0
217  1
218  76.
219  1,2,2,18,2,2,0,0
220  1
221  0.
222  1,2,2,18,3,1,0,0
223  5
224  4000.,32.,33.,34.,35.
225  1,2,2,19,1,1,0,0
226  2
227  1.,0.
228  1,2,2,19,2,1,0,0
229  1
230  80.
231  1,2,2,19,2,2,0,0
232  1
233  0.
234  1,2,2,19,3,1,0,0
235  5
236  4000.,32.,33.,34.,35.
237  1,2,2,20,1,1,0,0
238  2
239  0.,0.
240  1,2,2,20,2,1,0,0
241  1
242  78.
243  1,2,2,20,2,2,0,0
244  1
245  0.
246  1,2,2,20,3,1,0,0
247  5
248  4000.,32.,33.,34.,35.
@RESUME,P
```

Figure 12a. Example of Compressor Information Block (Cont'd)

84-5-16-46

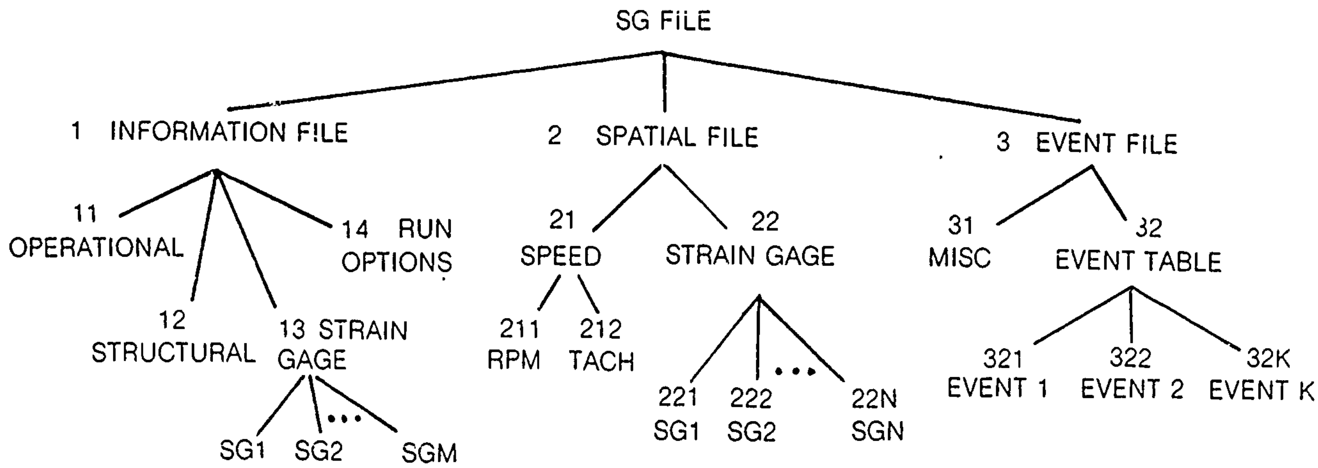


Figure 13. Strain-Gage File Structure

84-5-16-5

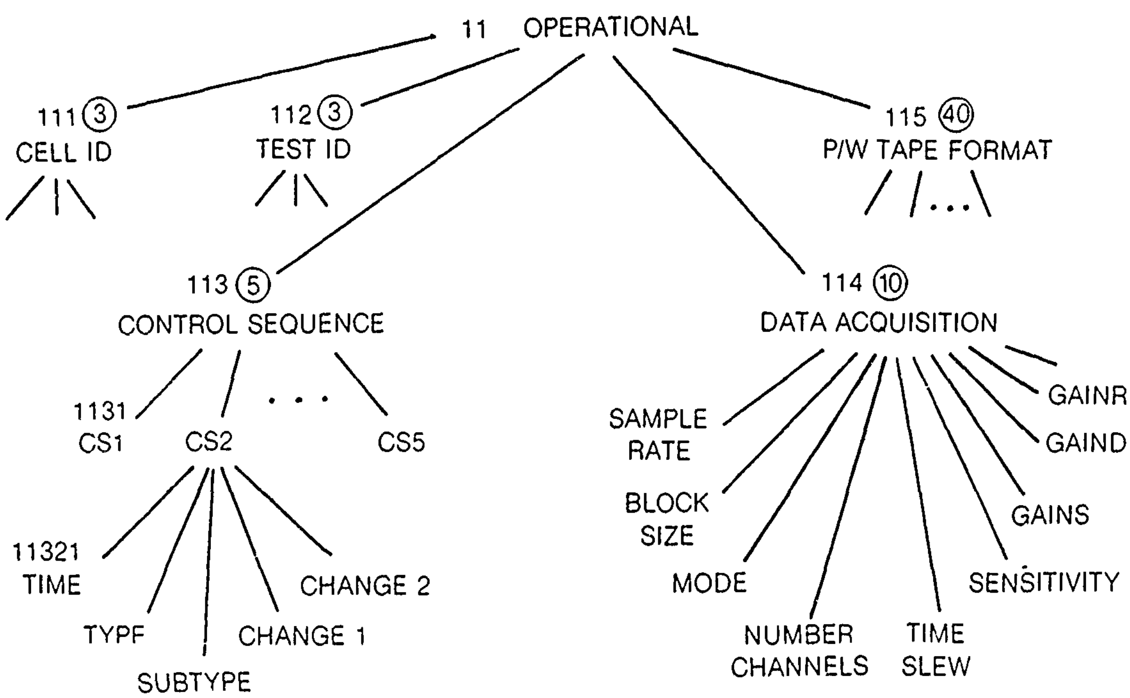


Figure 14. Information File (Operational Subdivision)

84-5-16-6

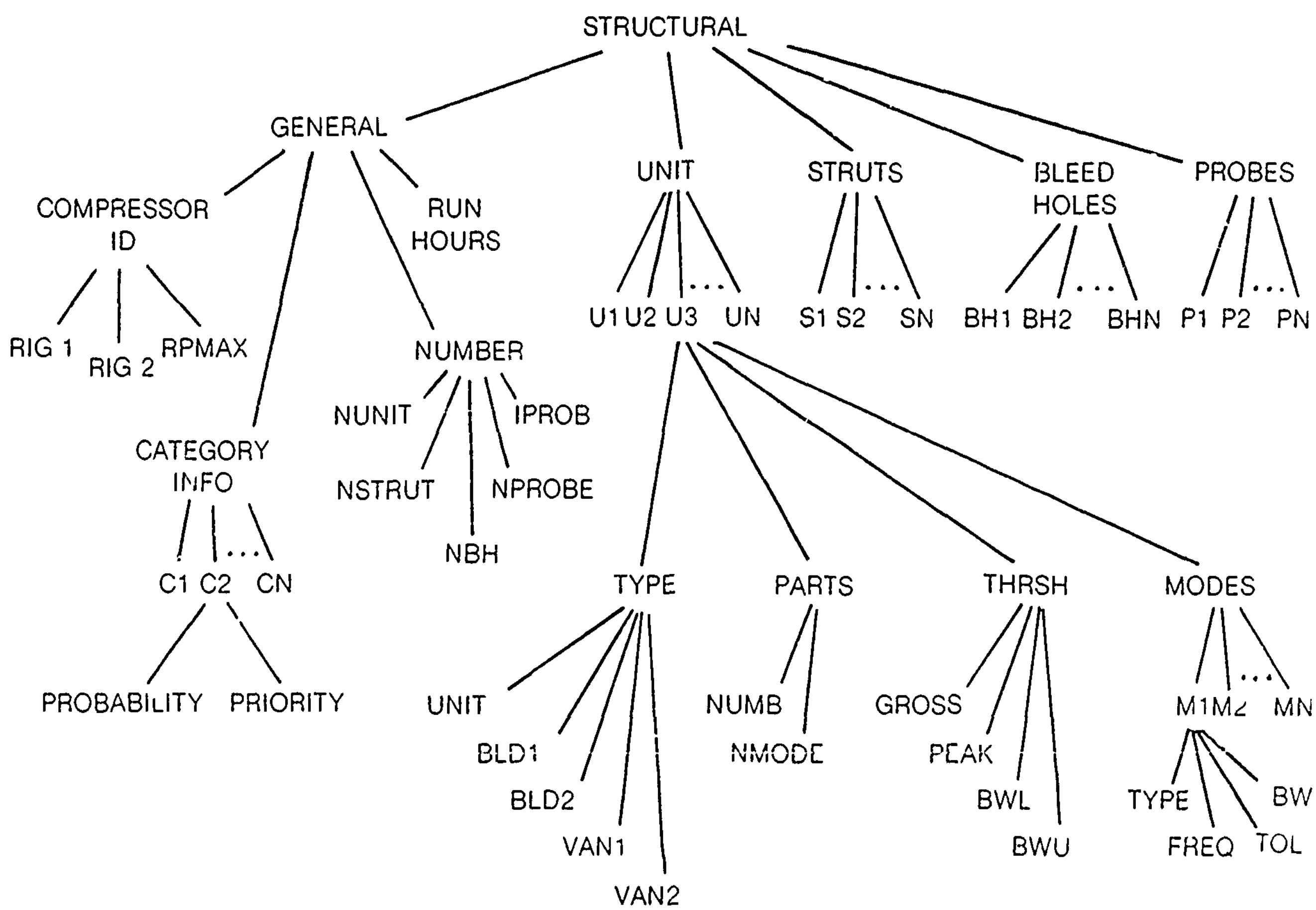


Figure 15. Information File (Structural Subdivision)

84-5 16-7

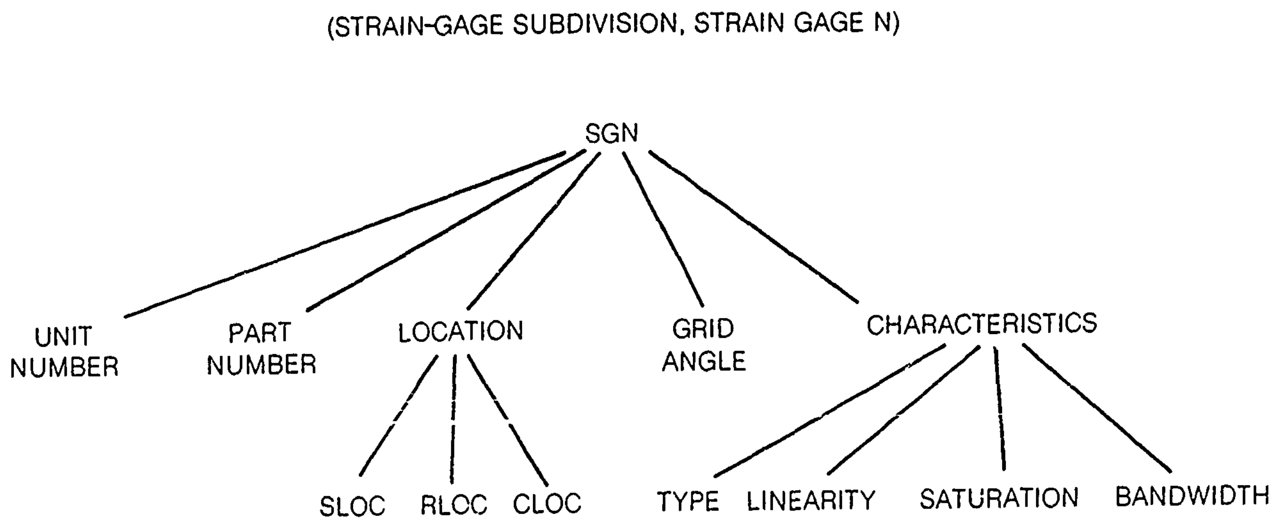


Figure 16. Information File (Strain-Gage Subdivision)

84-5-16-8

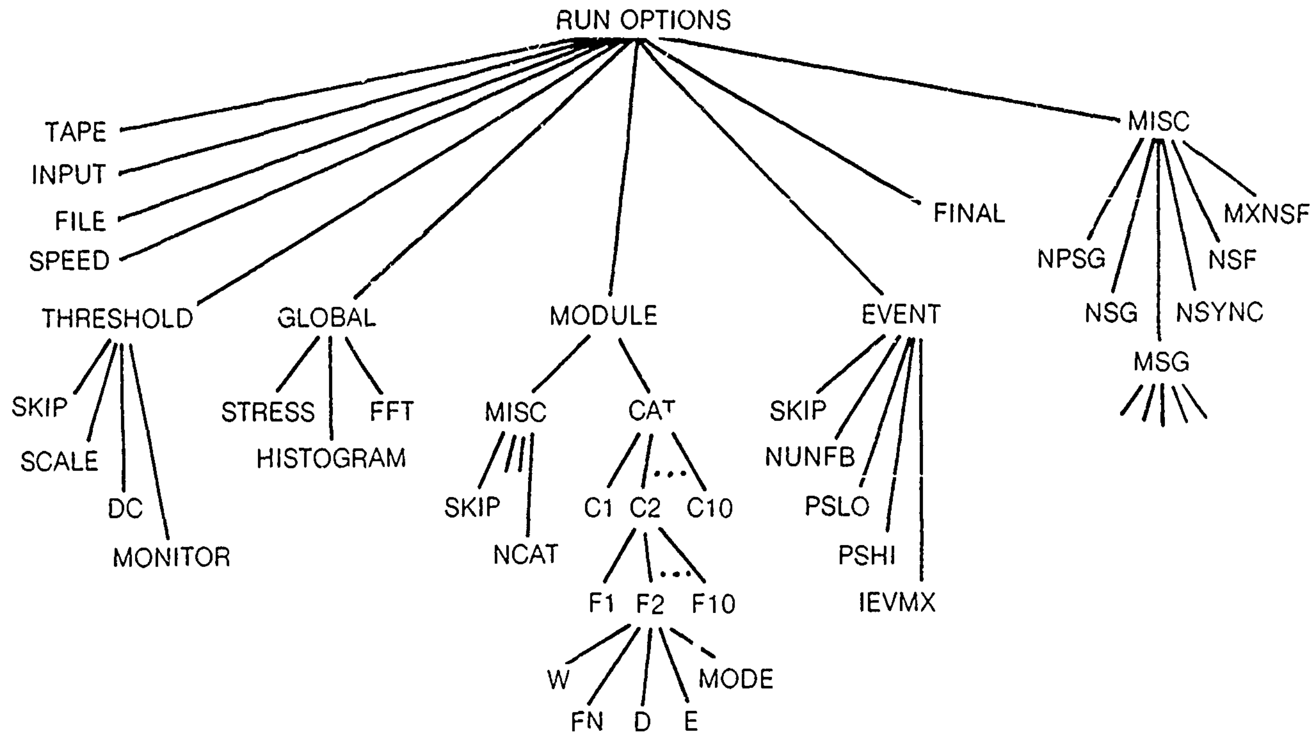


Figure 17. Information File (Run Option Subdivision)

84-5-16-9

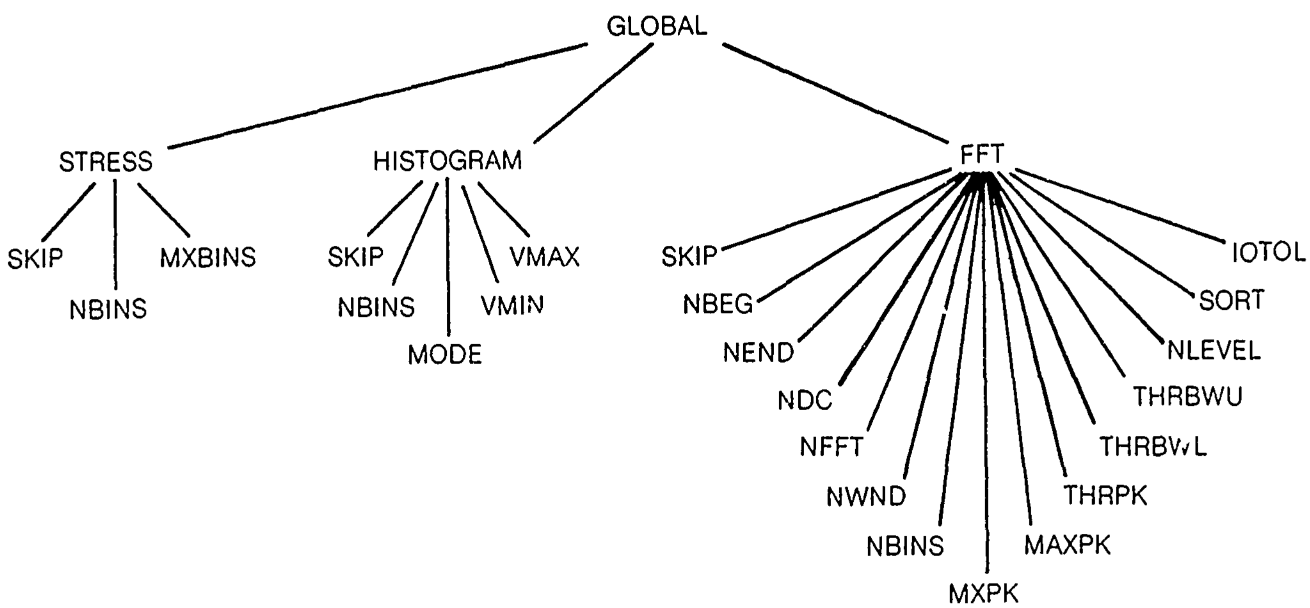


Figure 18. Information File (Run Option Subdivision, Global Feature Options)

84-5-16-10

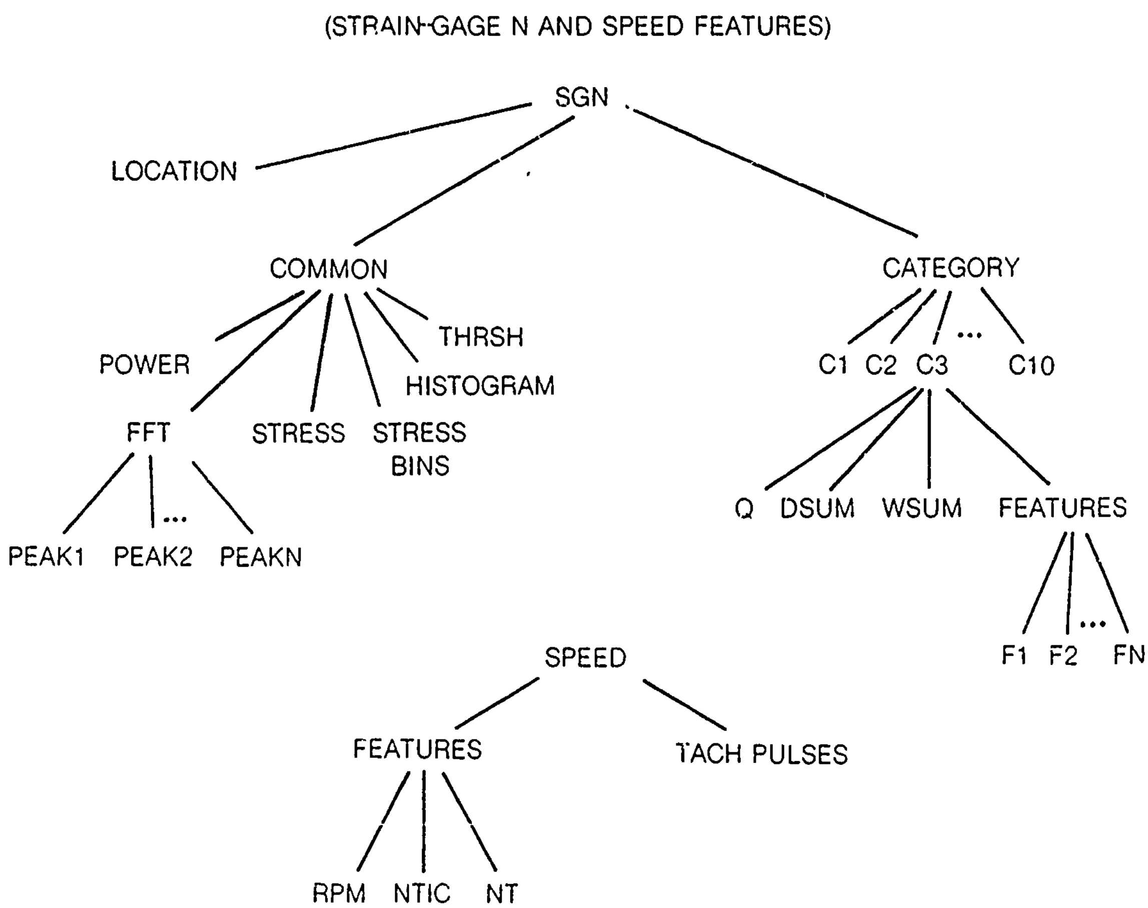


Figure 19. Spatial File

84-5-16-11

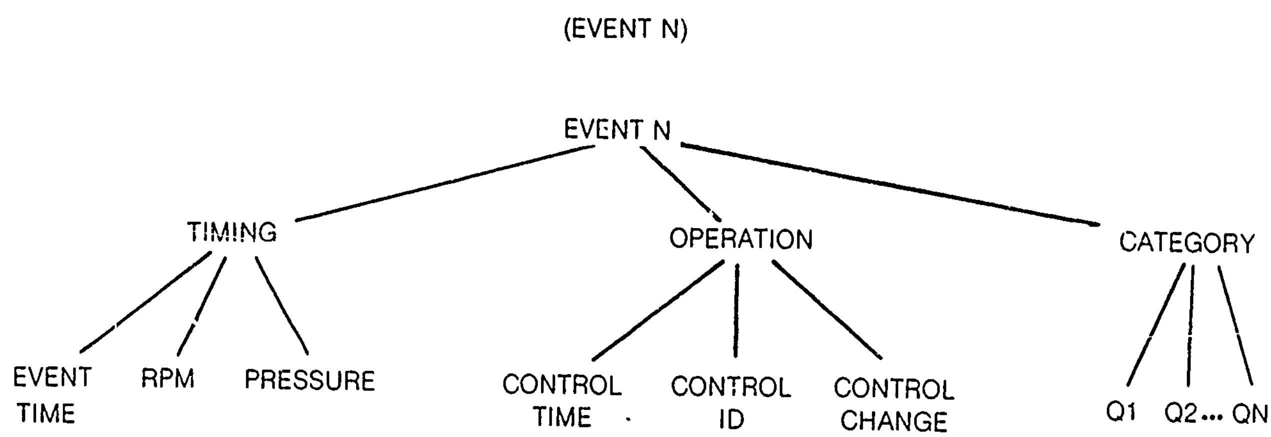


Figure 20. Event File

84-5-16-12

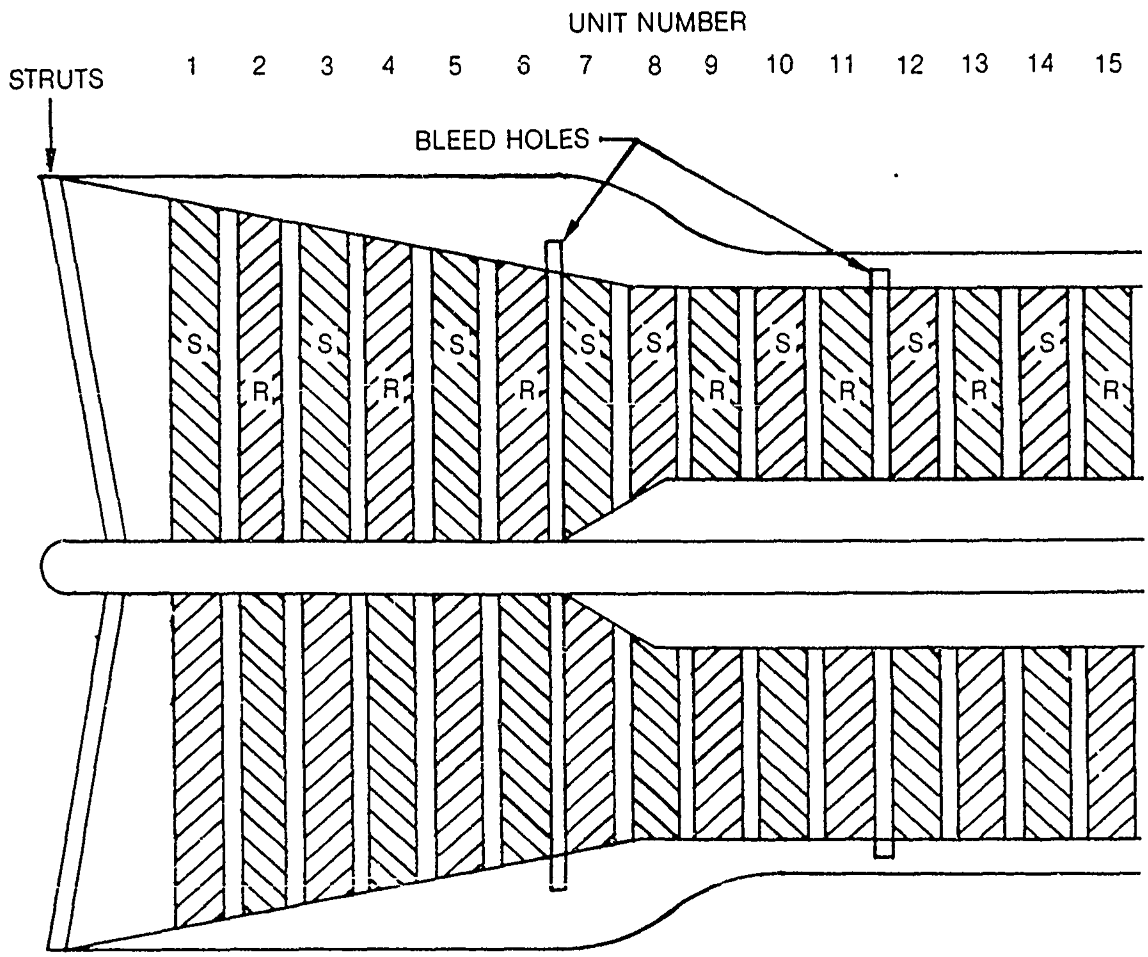


Figure 21. Generic Compressor

84-5-16-13

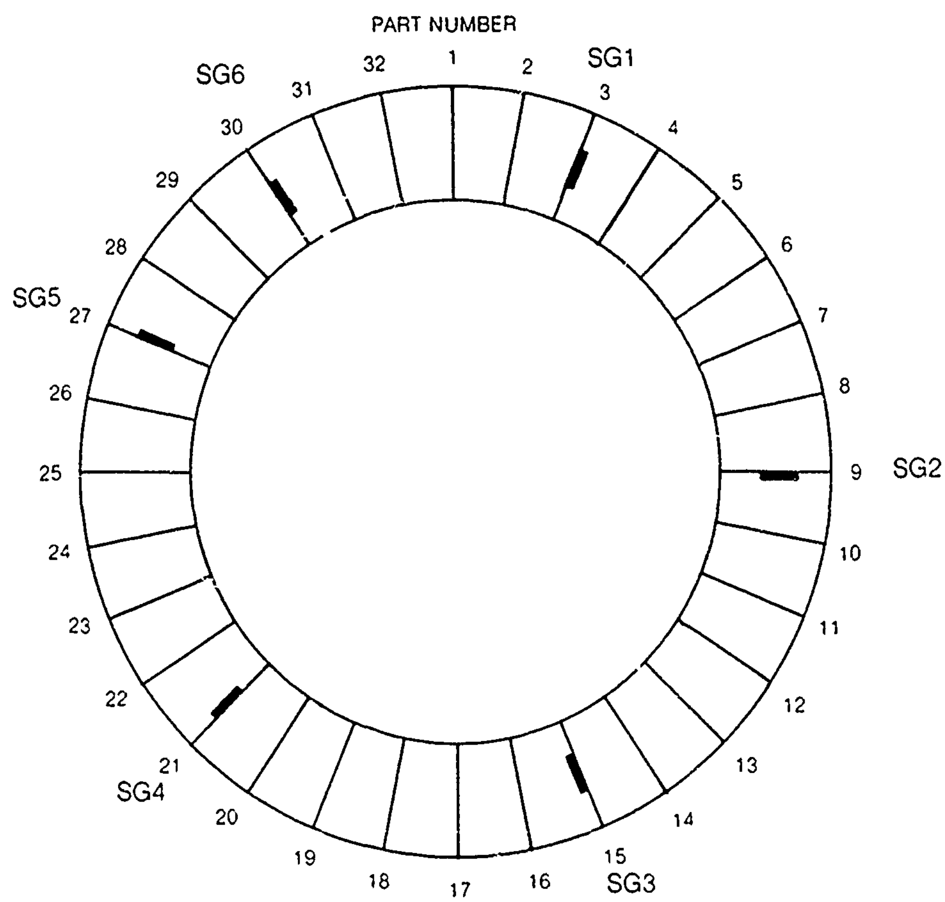


Figure 22. A Generic Unit With Strain-Gages

84-5-16-14

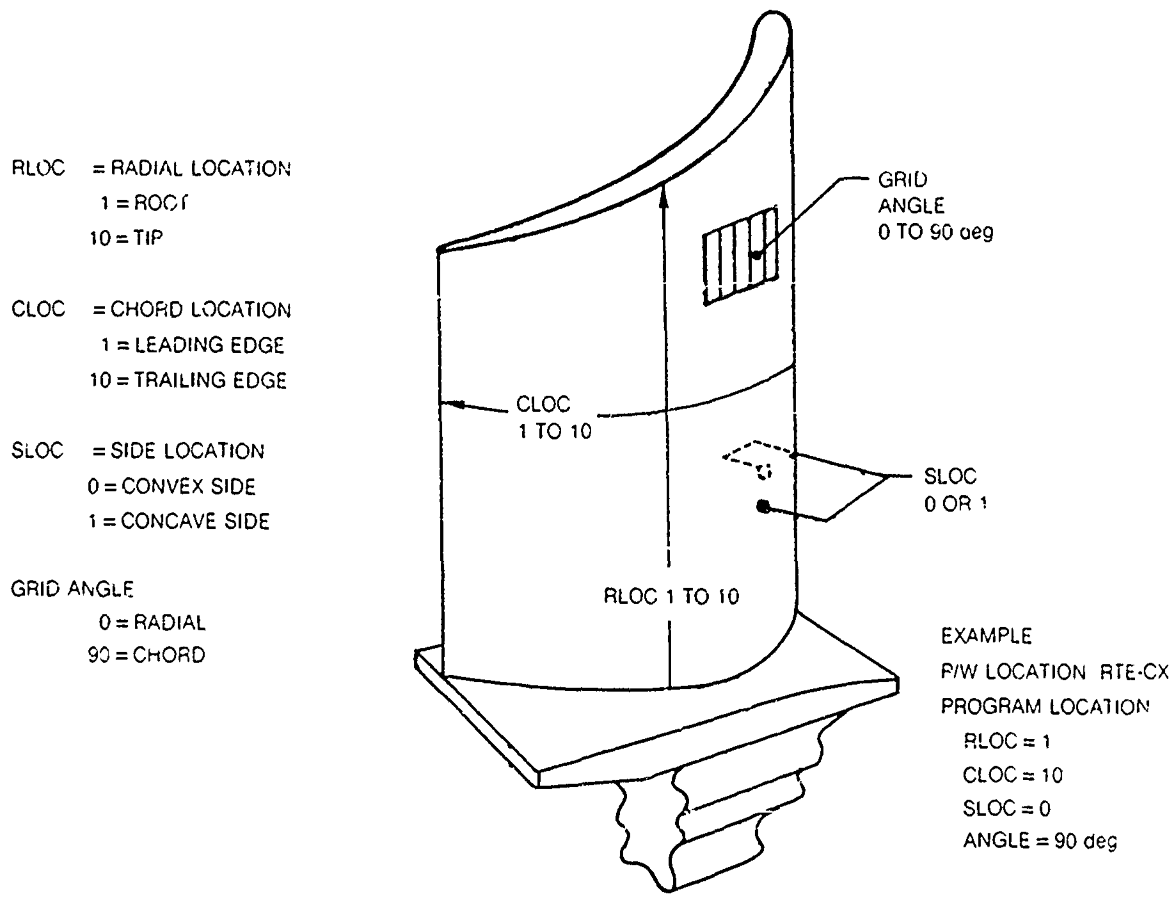


Figure 23. Strain-Gage Location on Part

84-5-16-15

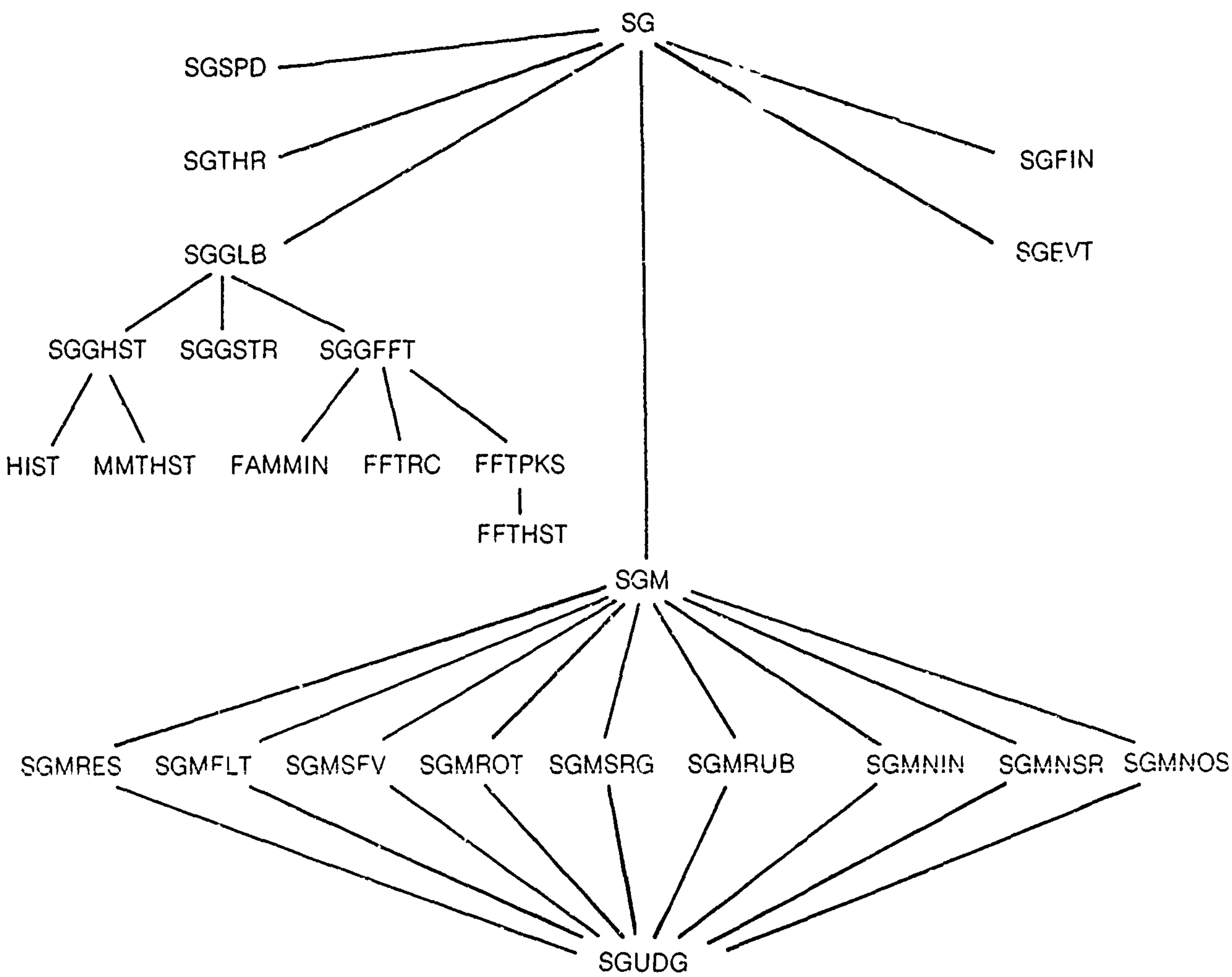


Figure 24. SG Classifier Structure

84-5-16-16

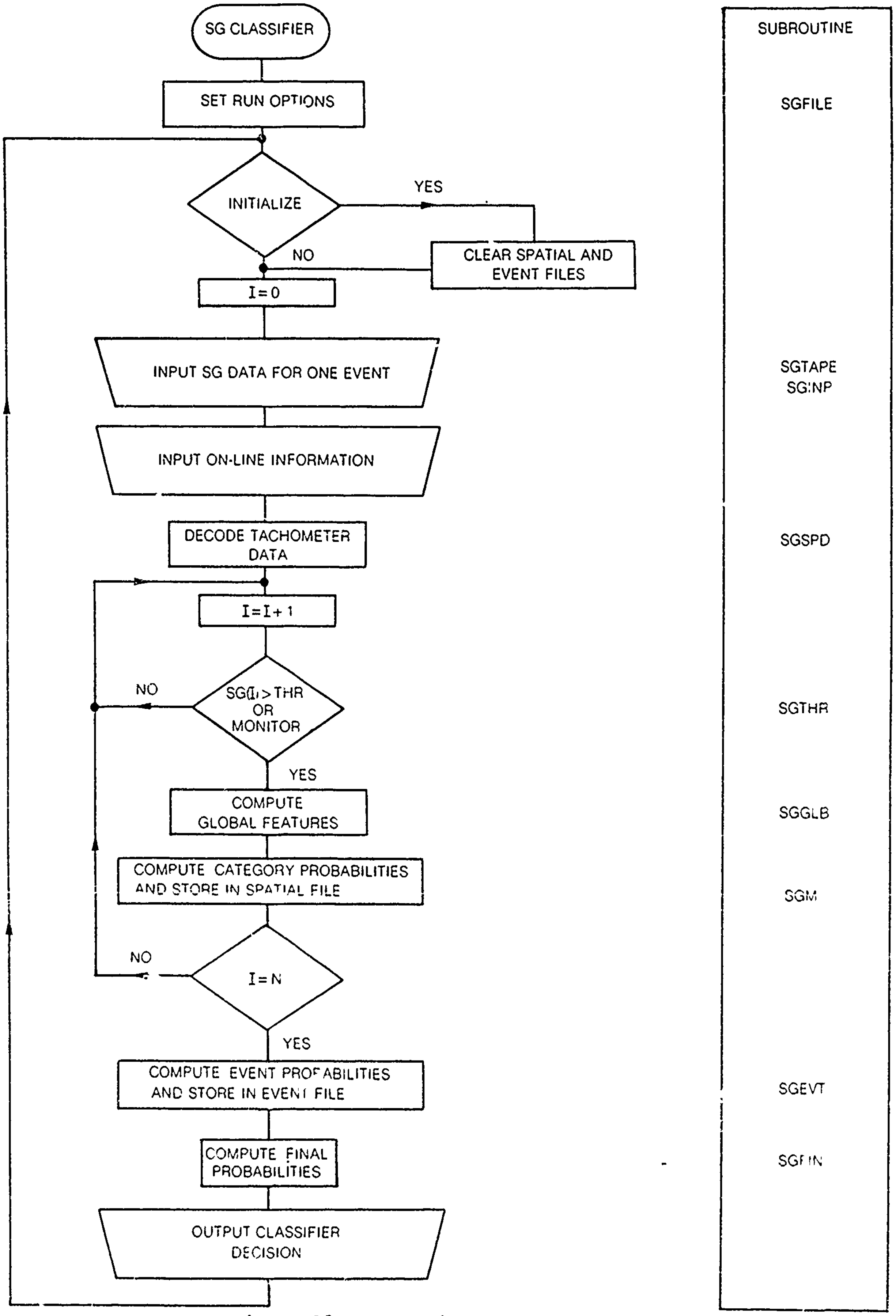
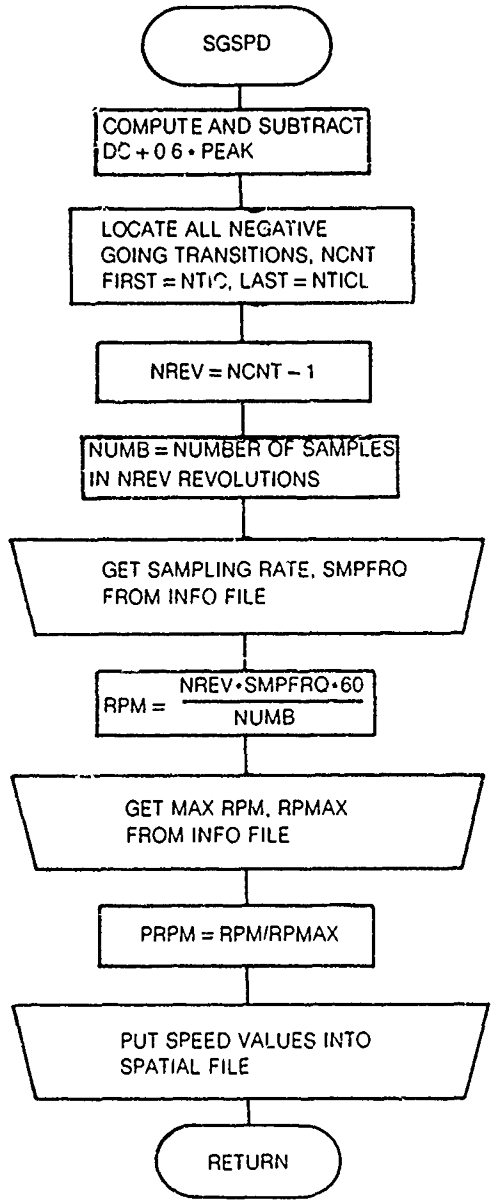


Figure 25. Flow Diagram for Subroutine SG

84-5-16-17

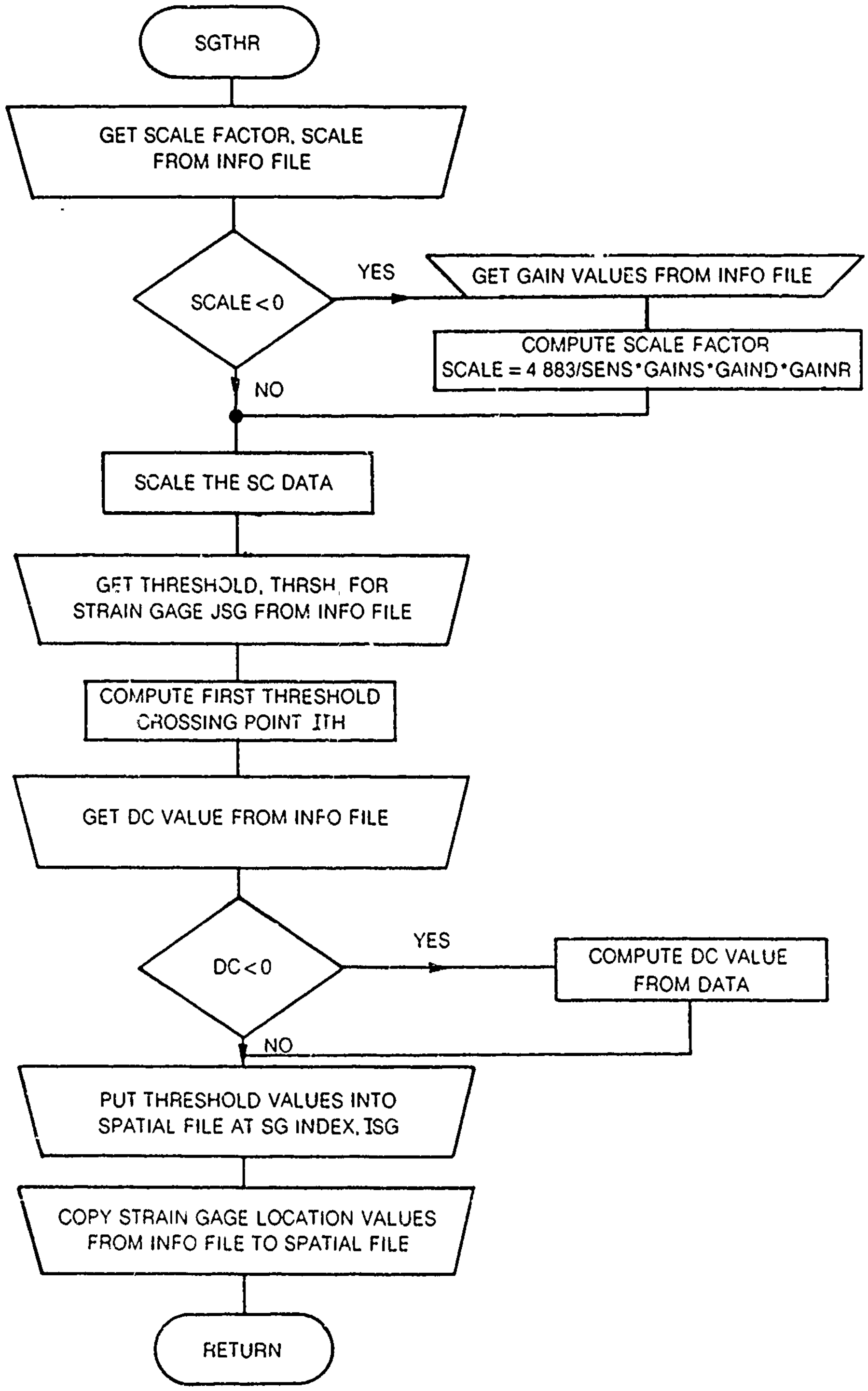


REQUIRED PARAMETERS	
SMPFRQ	1 1. 4. 1 0
RPMAX	1. 2. 1. 1. 3. 0

COMPUTED VALUES	
RPM NTIC NTICL NCNT PRPM	2 1. 1. 1 0 THRU 2. 1. 1 5. 0
TACHOMETER PULSE LOCATIONS	2. 1. 2 1. 0 THRU 2. 1. 2. 200. 0

Figure 26. Flow Diagram for Subroutine SGSPD

84–5–16–18

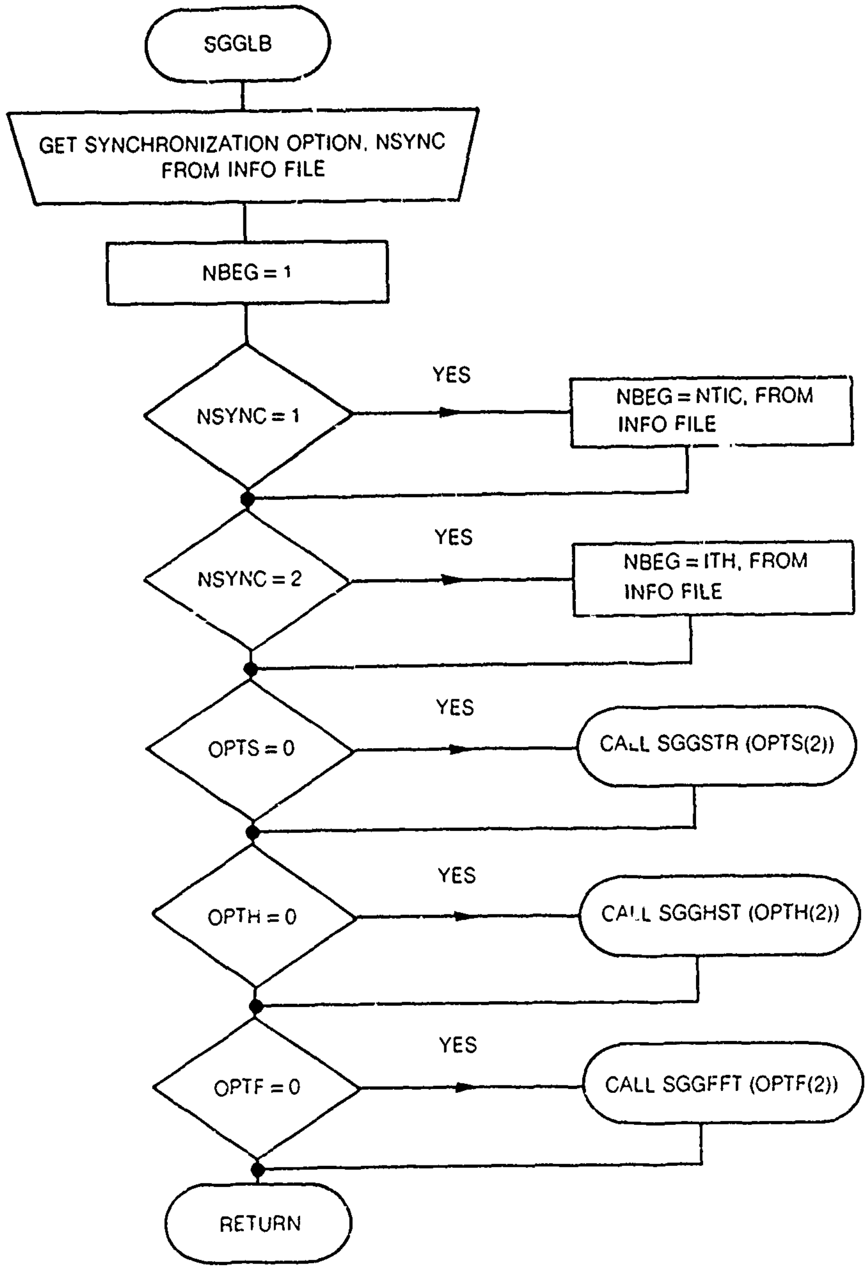


REQUIRED PARAMETERS	
SCALE	1, 4, 5, 2, 0
DC	1, 4, 5, 3, 0
SENS	1, 1, 4, 6, 0
GAINS	1, 1 4, 7, 0
GAIND	1, 1, 4 8 0
GAINR	1, 1, 4 9, 0
JUNIT	1, 3, JSG 1, 0
THRSH	1 2 2 JUNIT 3 1 0

COMPUTED VALUES	
ITH V(ITH) SCALE DC	2, 2 ISG, 2 6 1, 0 THRU 2 2 ISG 2 6 4, 0

Figure 27. Flow Diagram for Subroutine SGTHR

84–5–16- 19

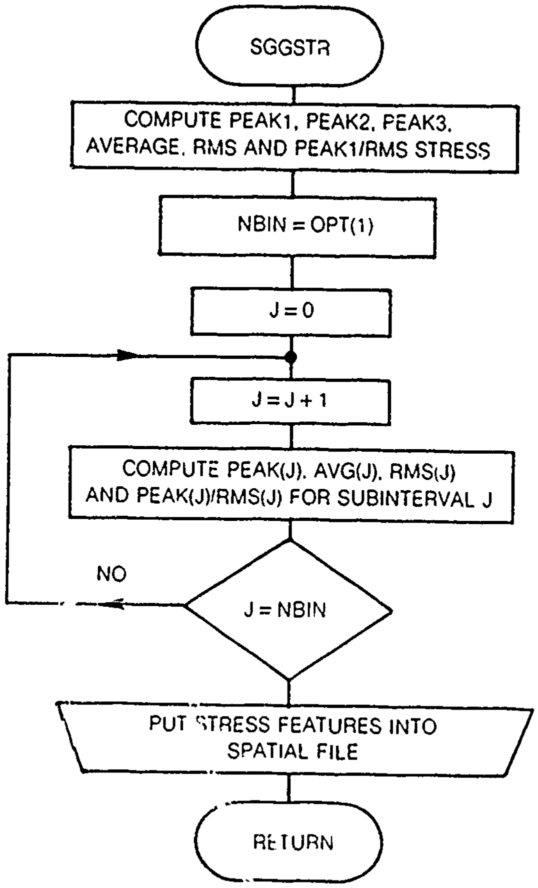


REQUIRED PARAMETERS	
NSYNC	1 4 10 4 0
NTIC	2, 1, 1, 2 0
ITH	2, 2, ISG 2, 6 1, 0
OPTS	1, 4 6, 1, 1, 0
OPTH	1 4 6, 2 1, 0
OPTF	1, 4, 6, 3, 1, 0

COMPUTED PARAMETERS
NONE

Figure 28. Flow Diagram for Subroutine SGGLB

84-5-16-20

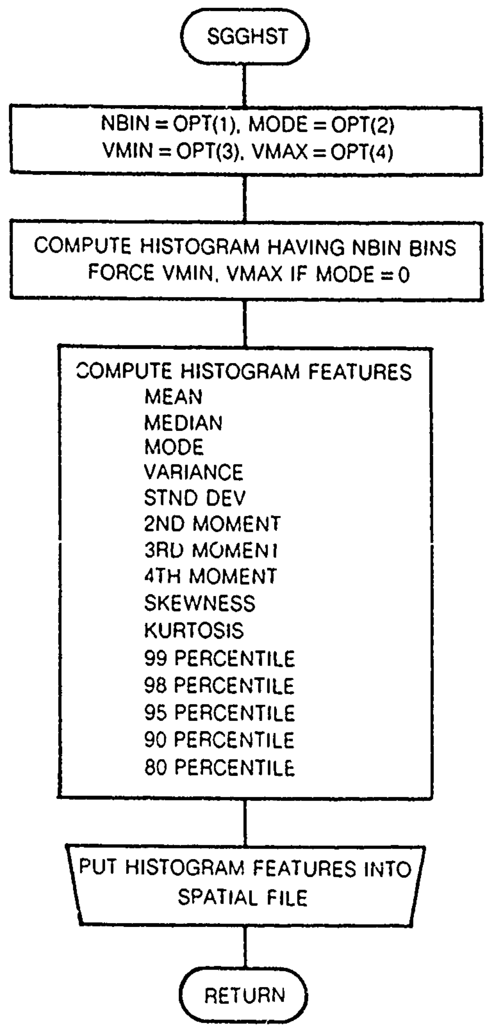


REQUIRED PARAMETERS	
NBIN MAXBIN	OPT(1) OPT(2)

COMPUTED PARAMETERS	
STRP	2 2, ISG 2
NTRP	3 1 0
STR2	TO
NTR2	2 2 ISG 2
STR3	3 14 0
NTR3	
STRA	
STRR	
STRP/STRR	
SUM	
VARP	
VARA	
VARR	
VARS	
PEAK(J)	2 2 ISG 2 4
AVG(J)	J 1, 0
RMS(J)	FOR J = 1 NBIN
SINE(J)	

Figure 29. Flow Diagram for Subroutine SGGSTR

84–5–16–21



REQUIRED PARAMETERS	
NBIN MODE VMIN VMAX	OPT(1) OPT(2) OPT(3) OPT(4)

COMPUTED PARAMETERS	
NBIN MODE VMIN VMAX MEAN ⋮ M80	2 2.ISG 2 5 1 0 TO 2.2.ISG.2.5 19.0

Figure 30. Flow Diagram for Subroutine SGGHST

84-5-16-22

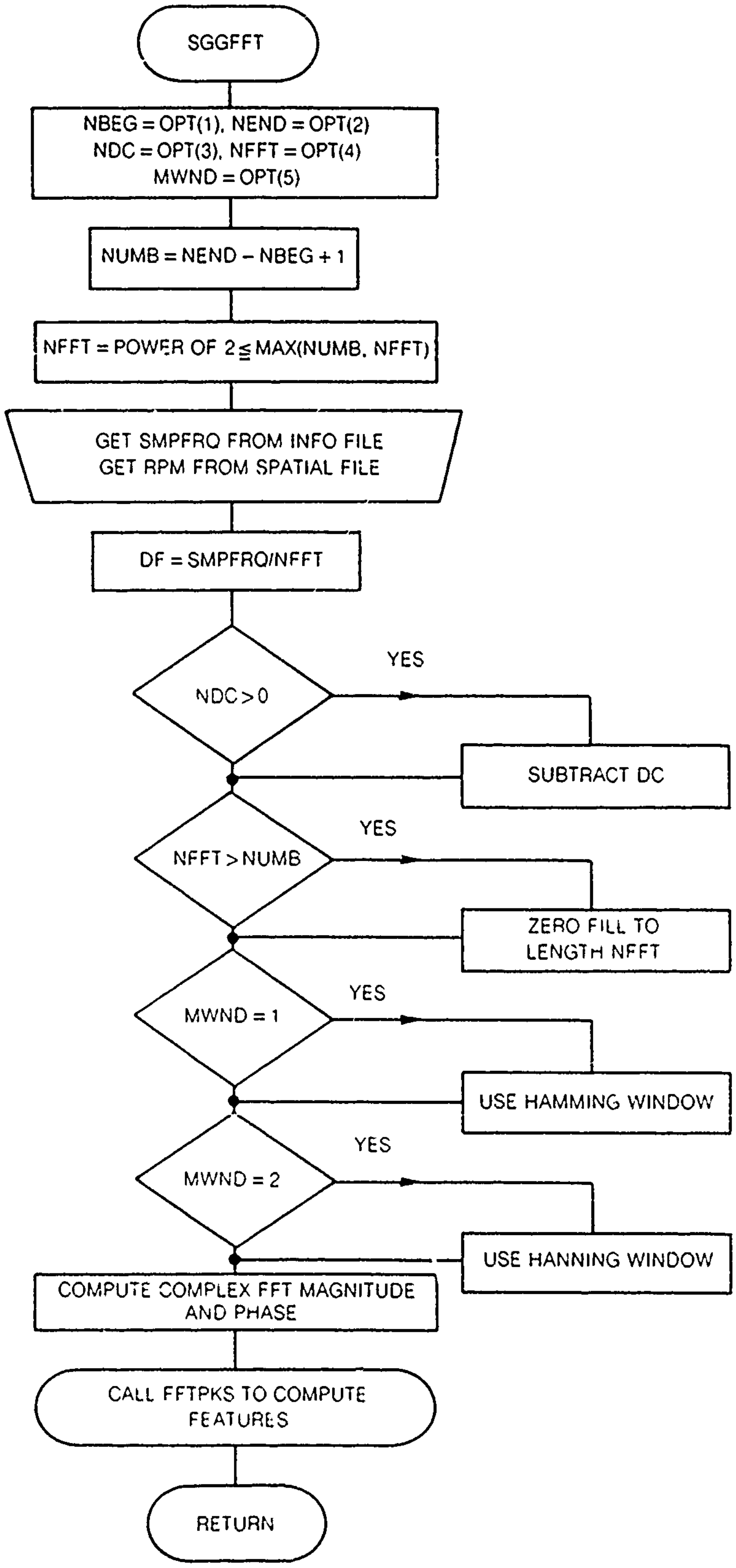


Figure 31. Flow Diagram for Subroutine SGGFFT

84-5-16-23

FLOW DIAGRAM FOR SUBROUTINE FFTPKS

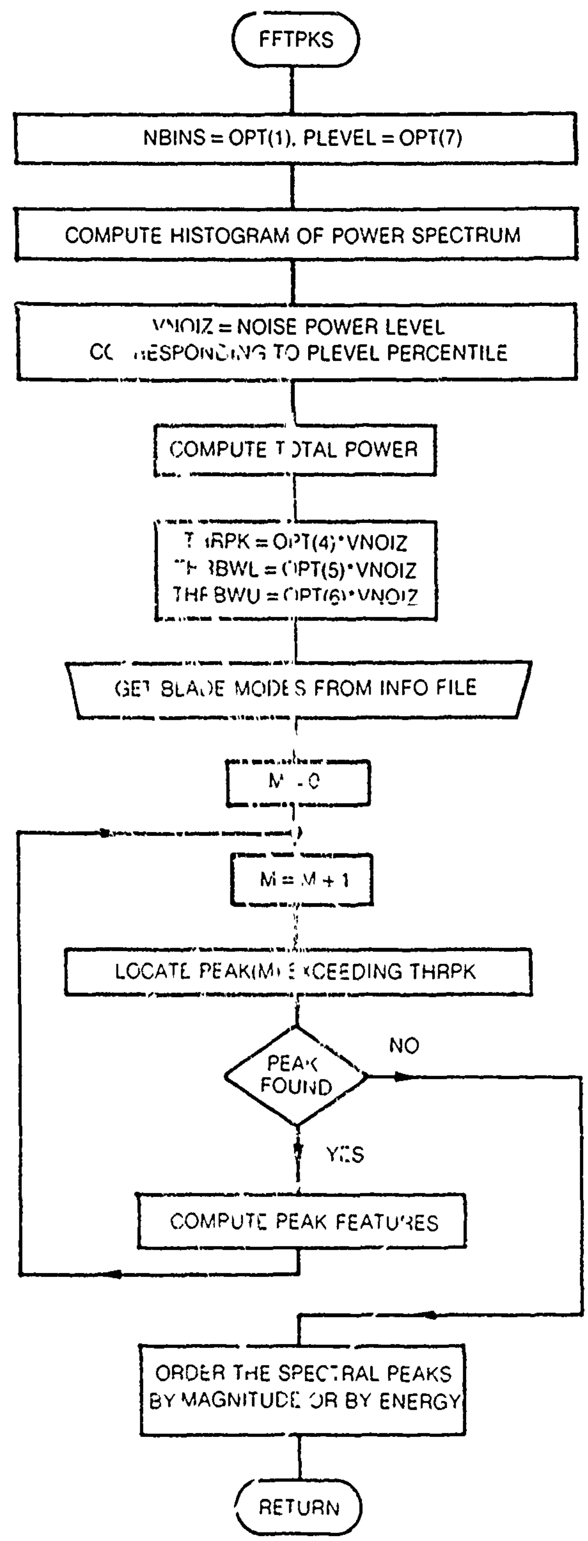


Figure 32. Flow Diagram for Subroutine FFTPKS

84-5-16-24

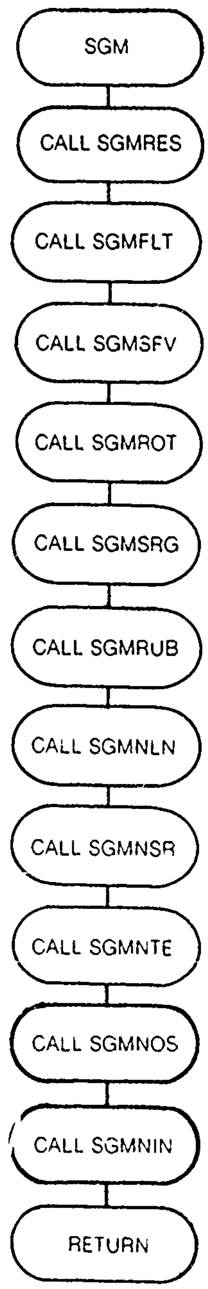


Figure 33. Flow Diagram for Subroutine SGM

84-5-16-25

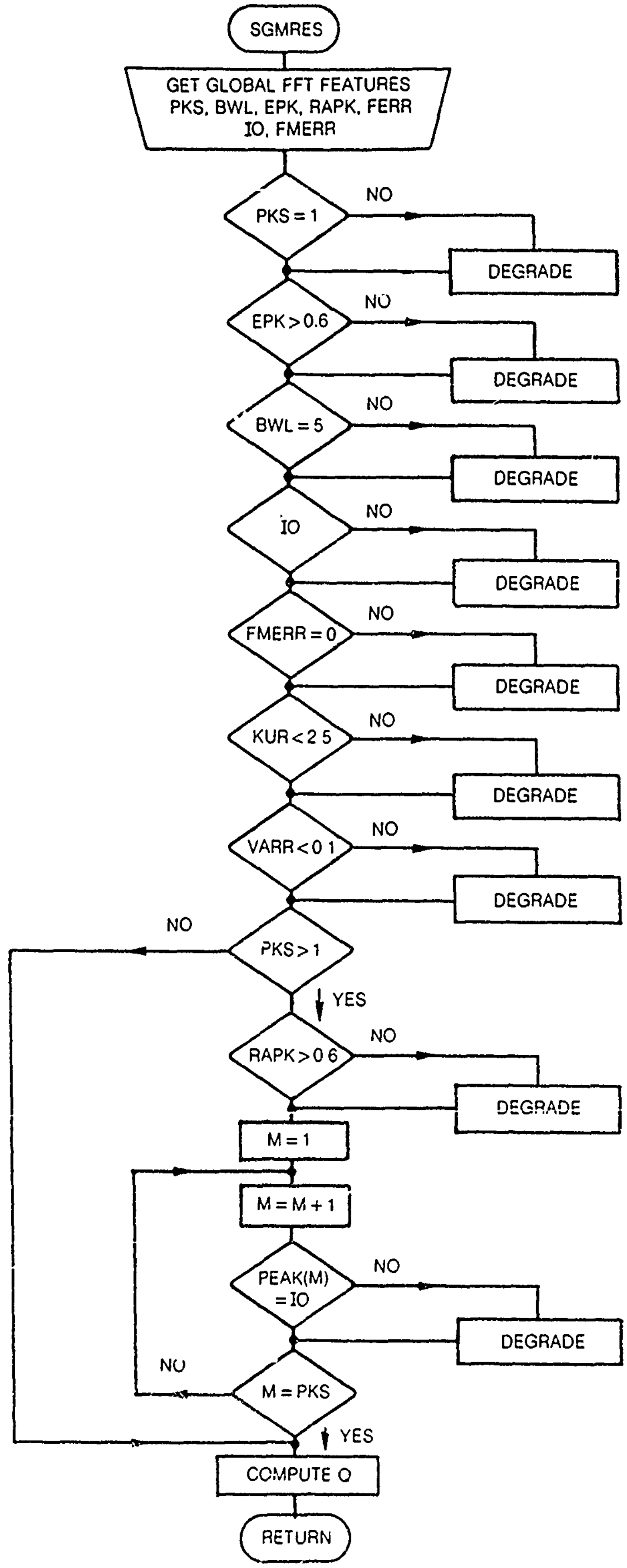


Figure 34. Flow Diagram for Subroutine SGMRES

84-5-16-26

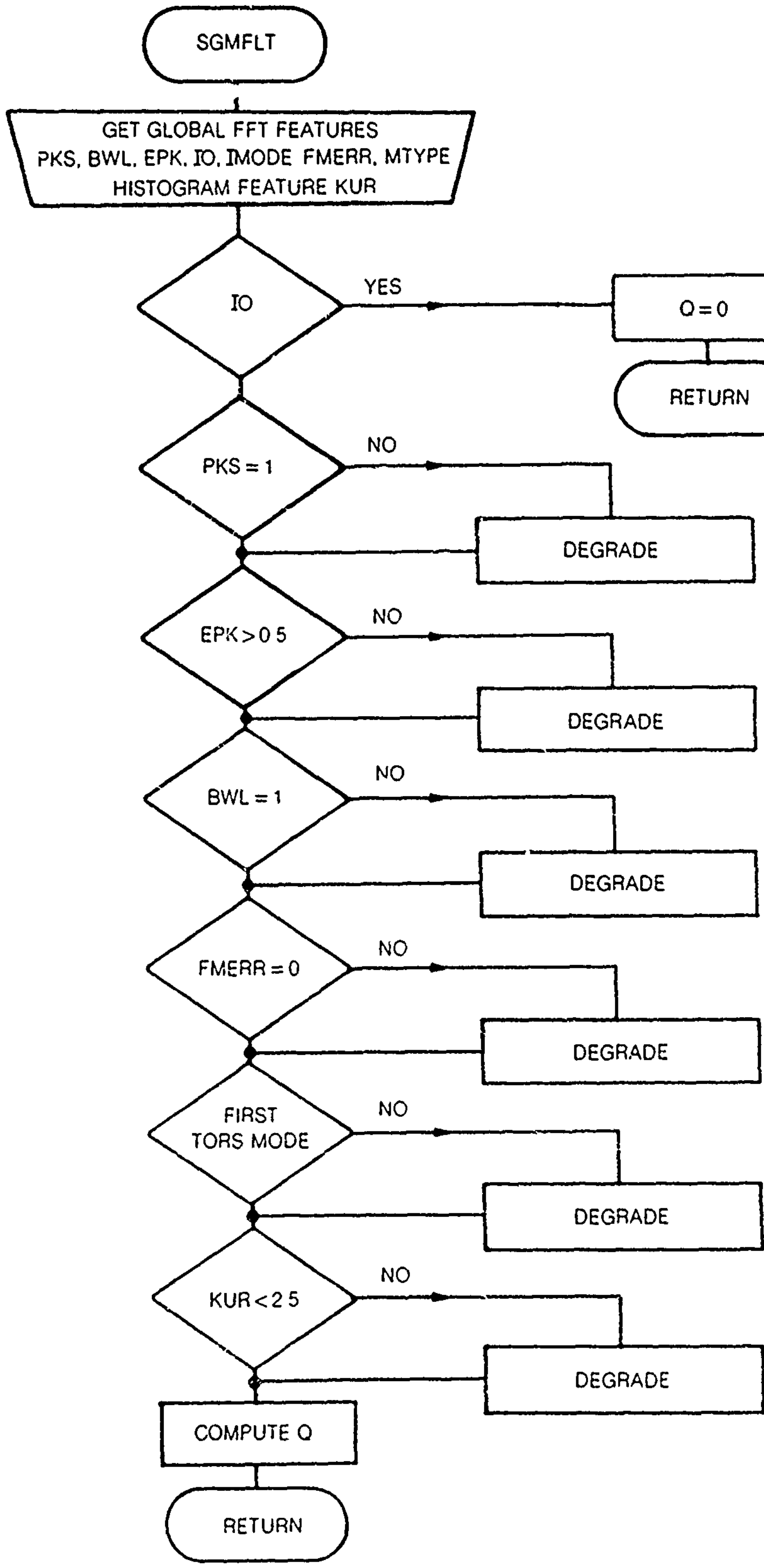


Figure 35. Flow Diagram for Subroutine SGMFLT

84-5-16-27

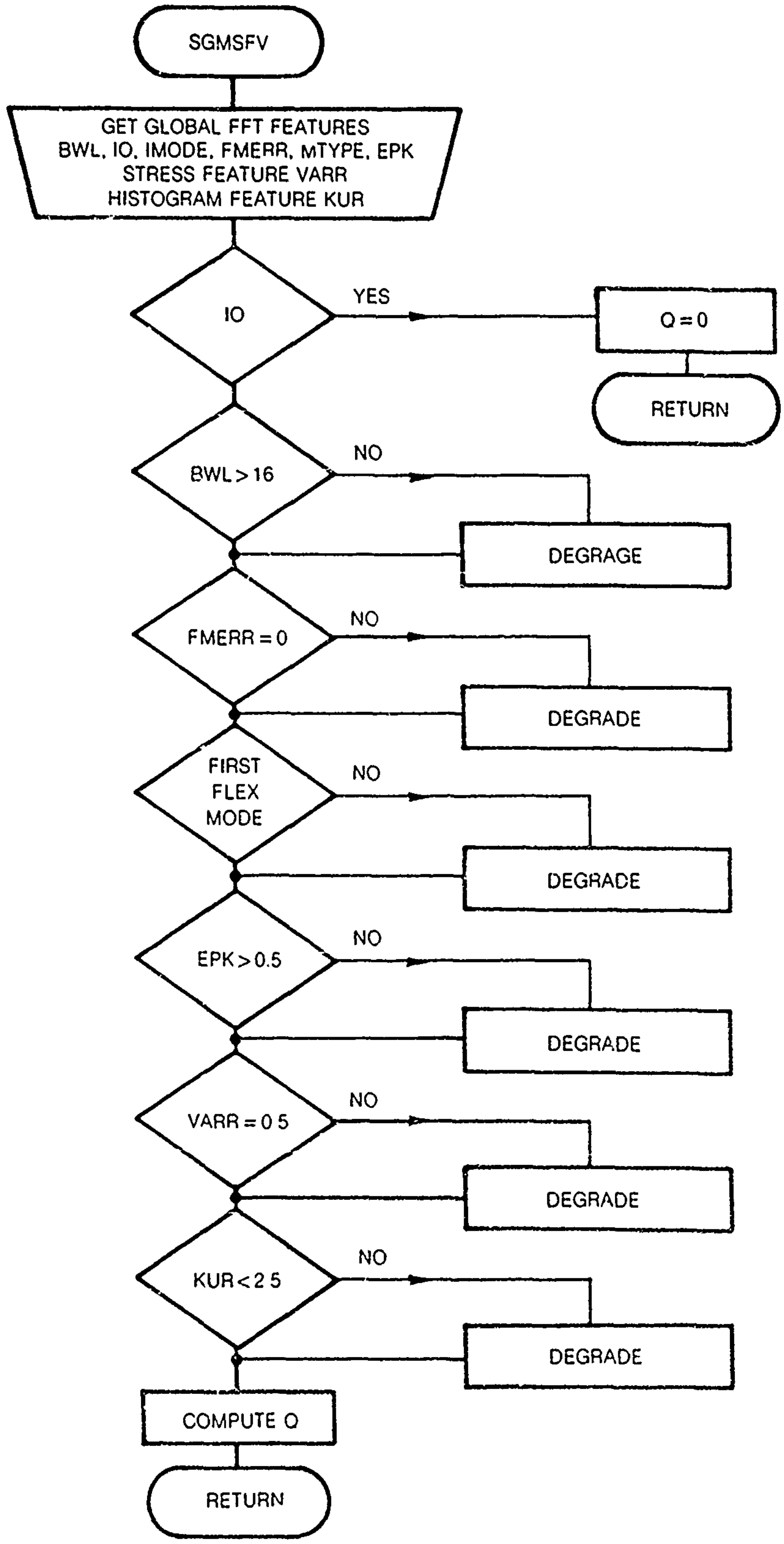


Figure 36. Flow Diagram for Subroutine SGMSFV

85-3-55-2

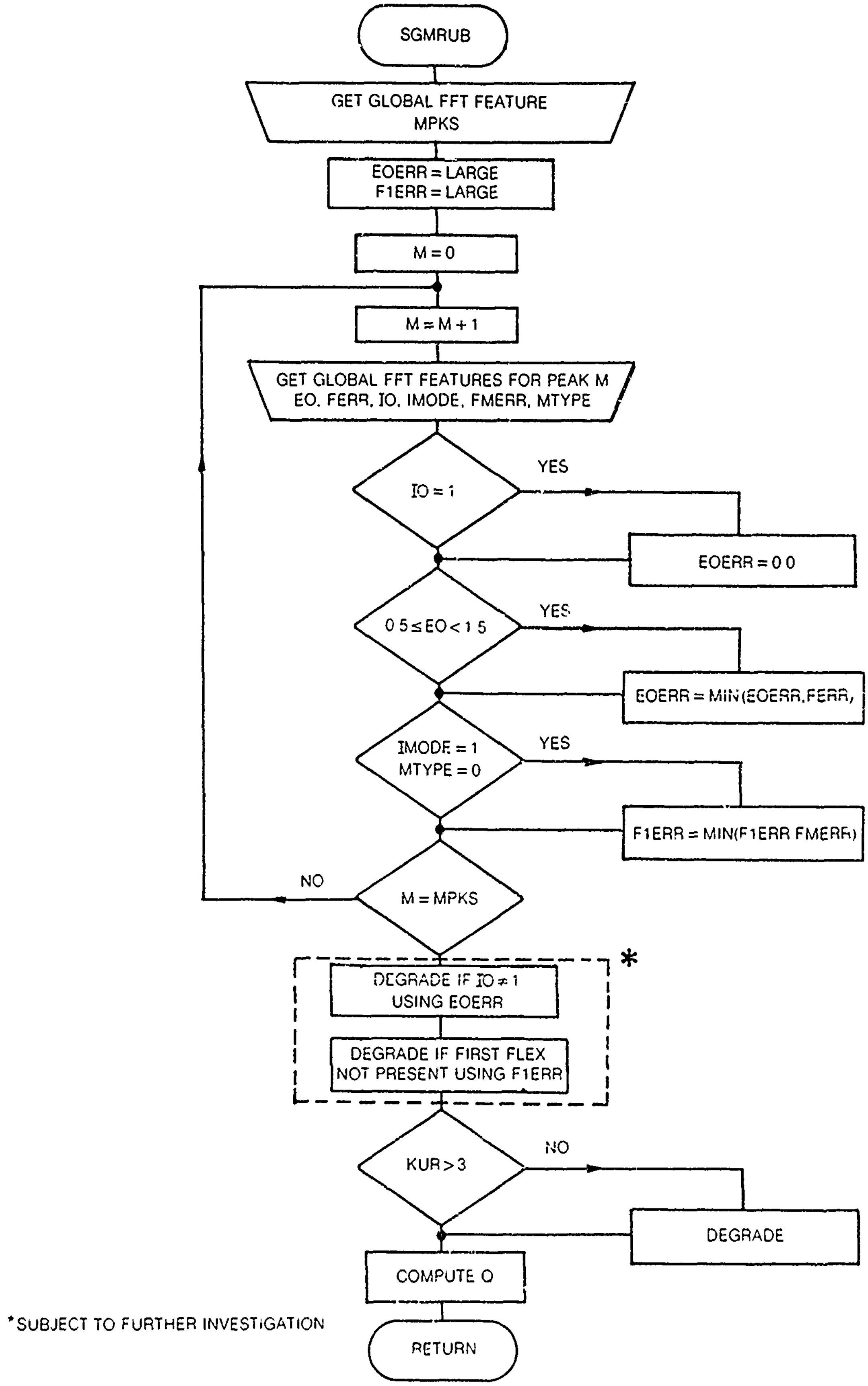


Figure 37. Flow Diagram for Subroutine SGMRUB

84-5-16-29

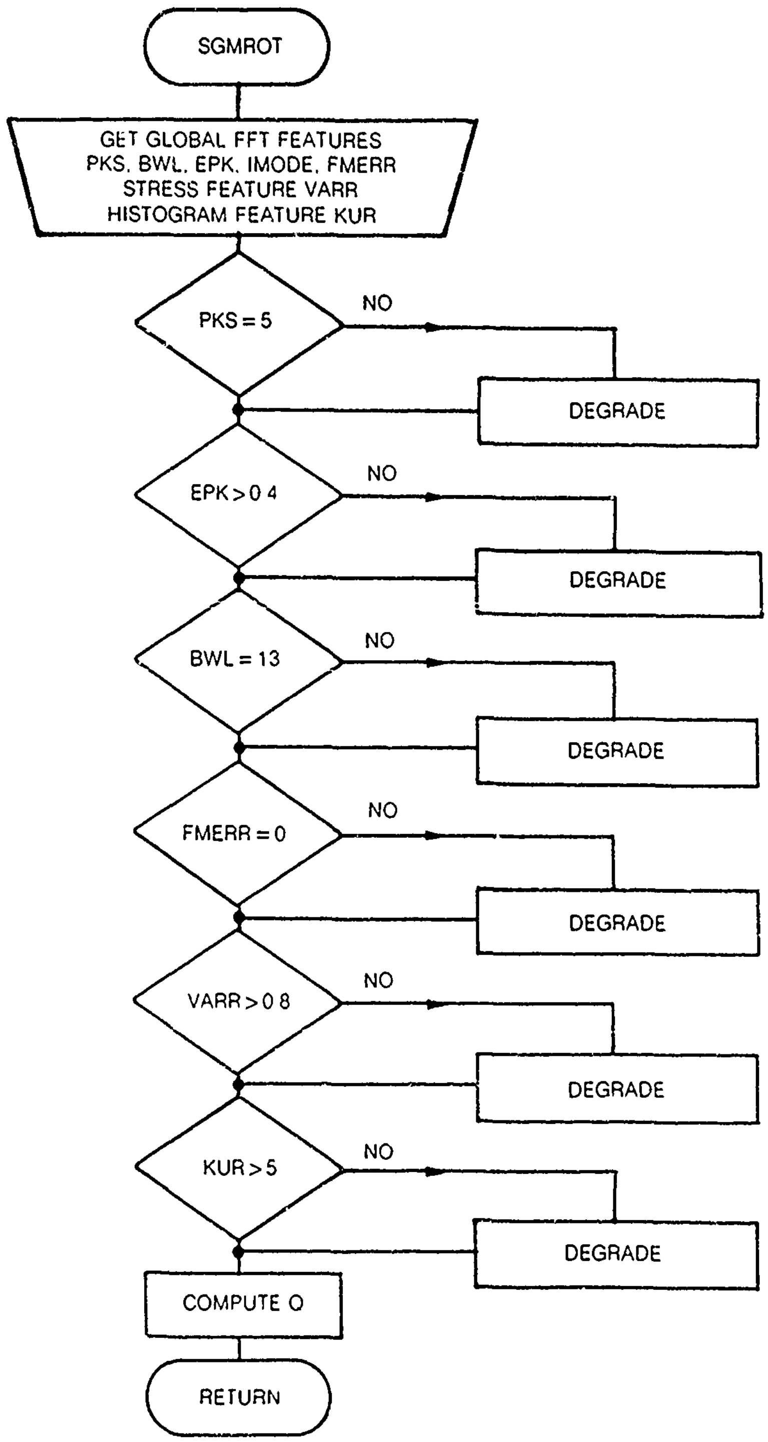


Figure 38. Flow Diagram for Subroutine SGMROT

84-5-16-30

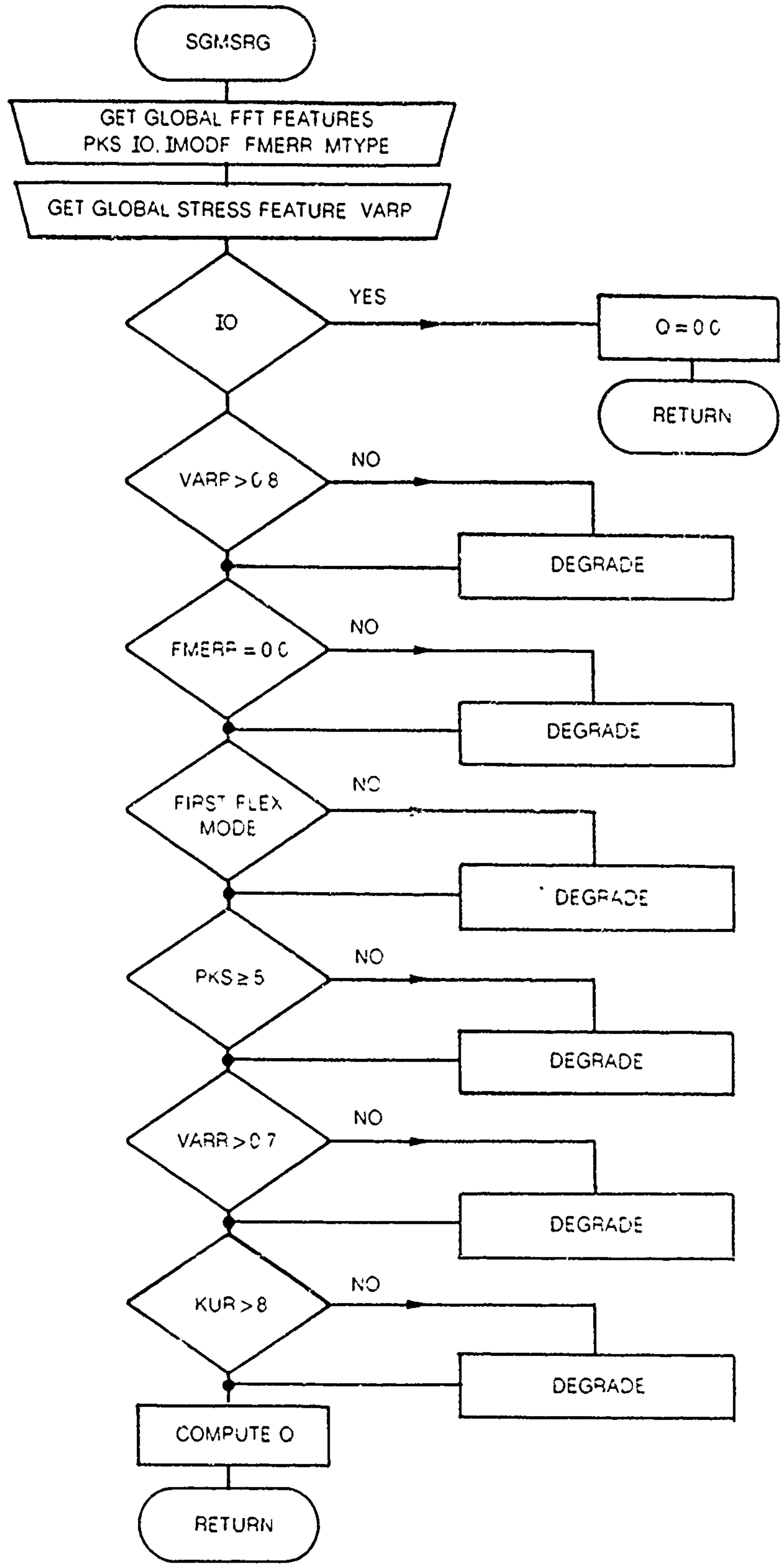


Figure 39. Flow Diagram for Subroutine SGMSRG

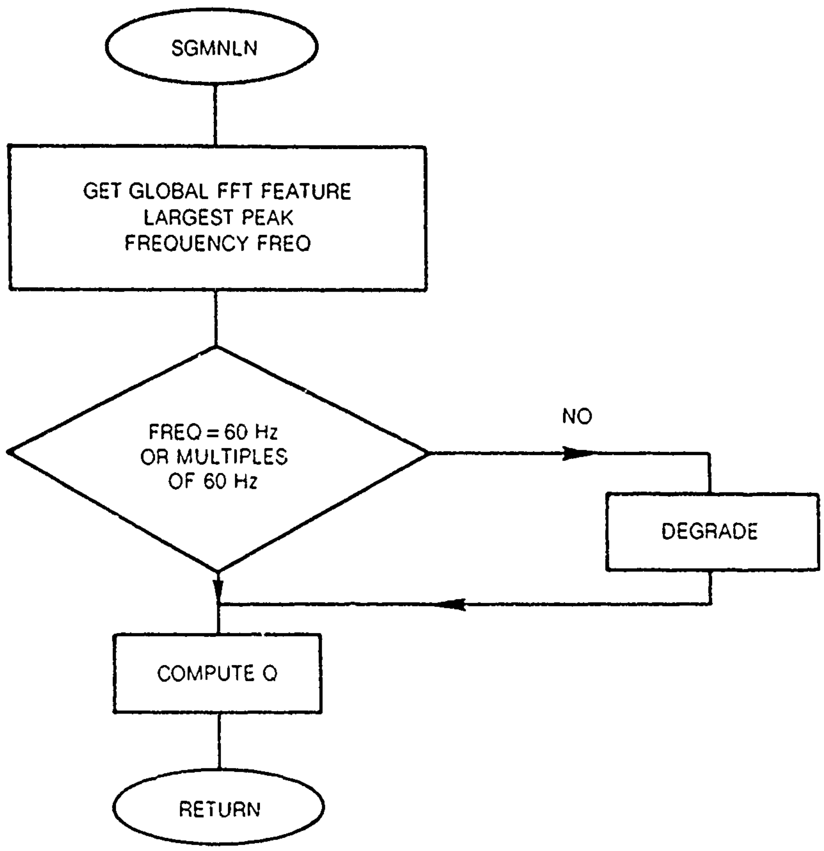


Figure 40. Flow Diagram for Subroutine SGMNLN

85-3-55-5

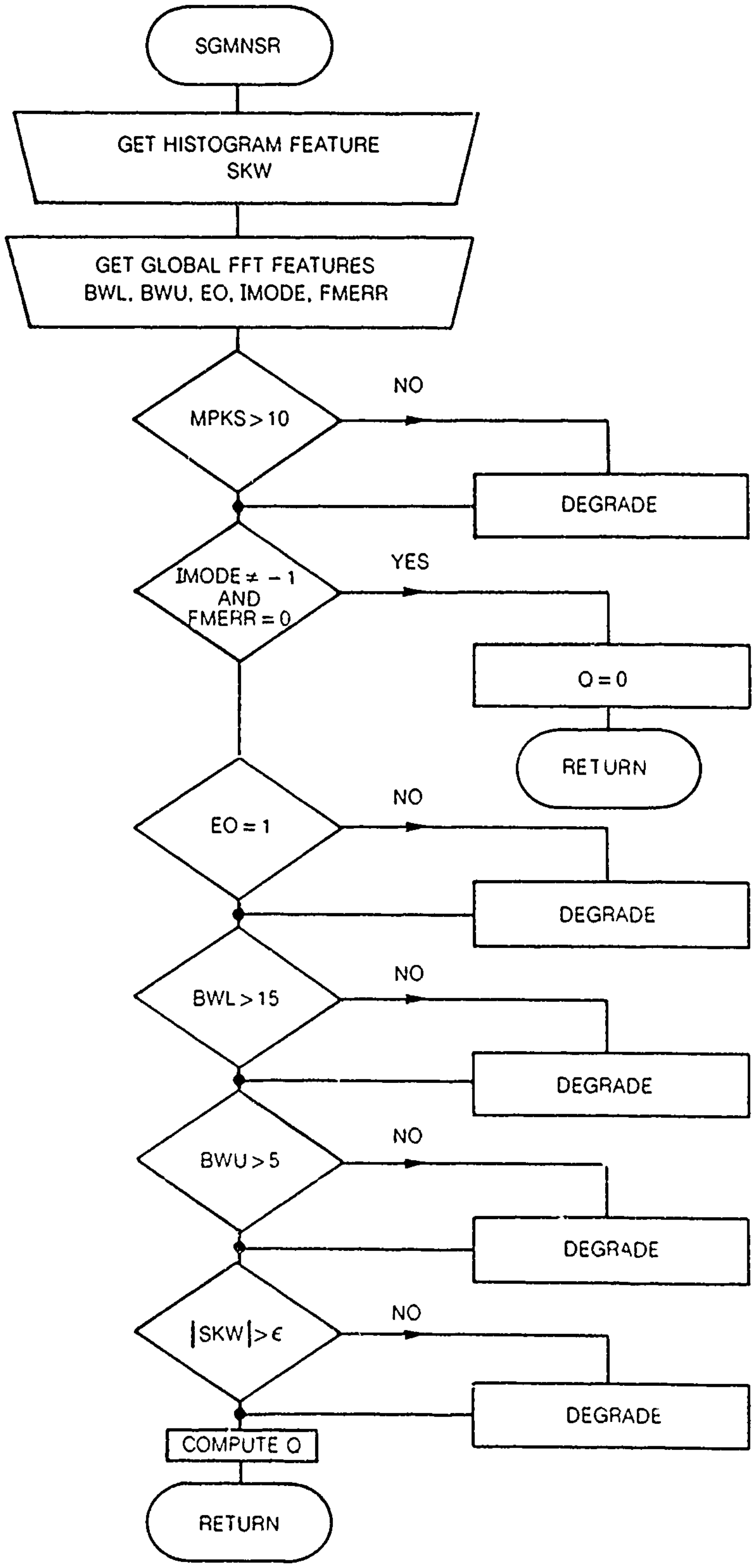


Figure 41. Flow Diagram for Subroutine SGMNSR

84–5–16–33

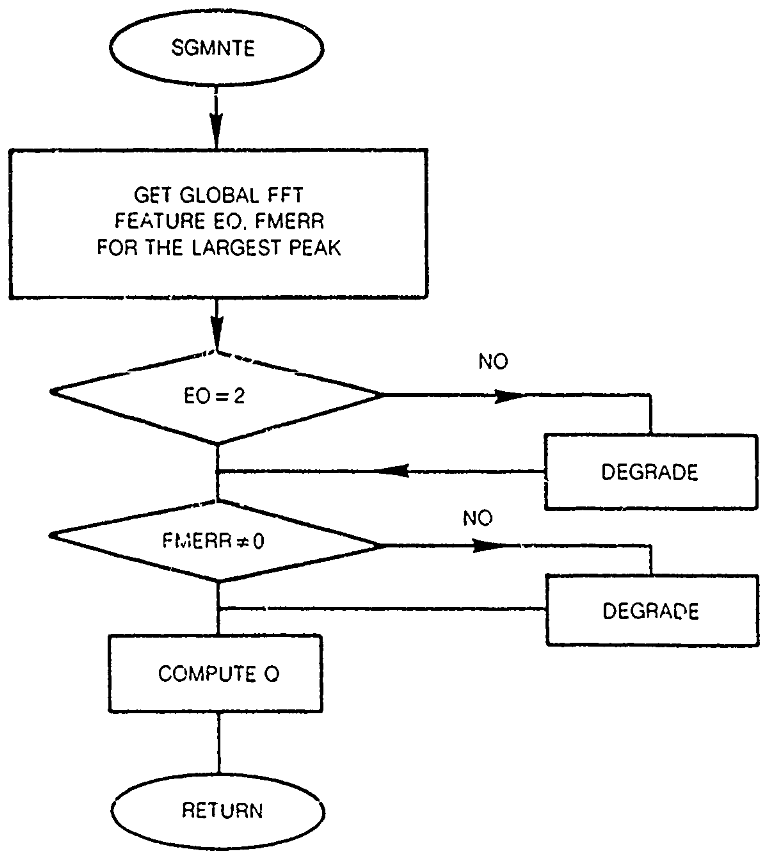


Figure 42. Flow Diagram for Subroutine SGMNTE

85–3–55–4

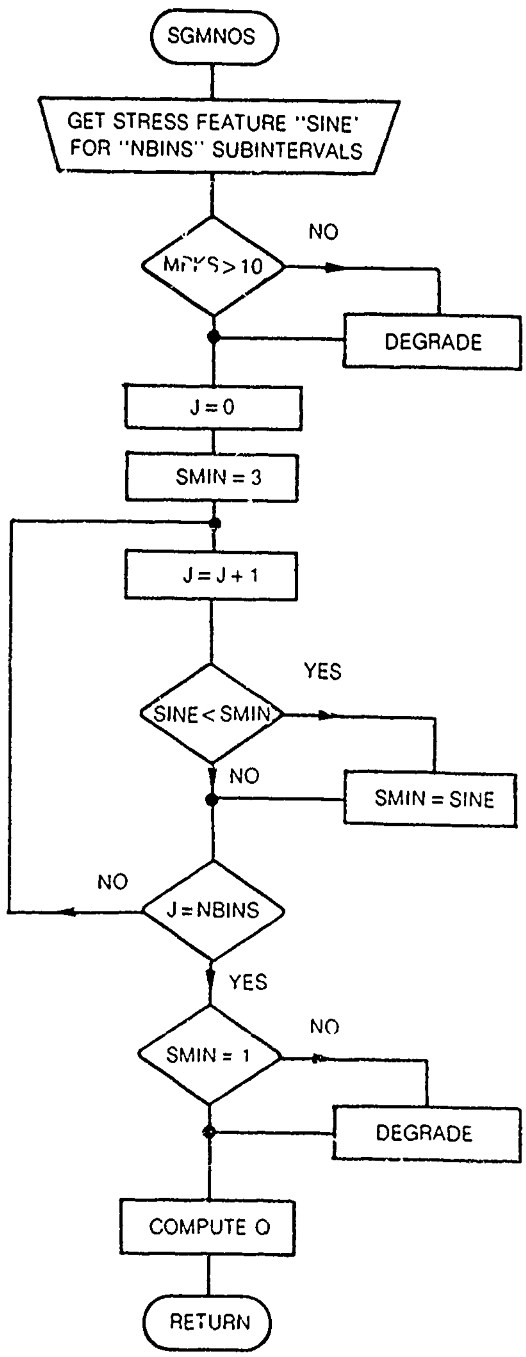


Figure 43. Flow Diagram for Subroutine SGMNOS

84–5–16–34

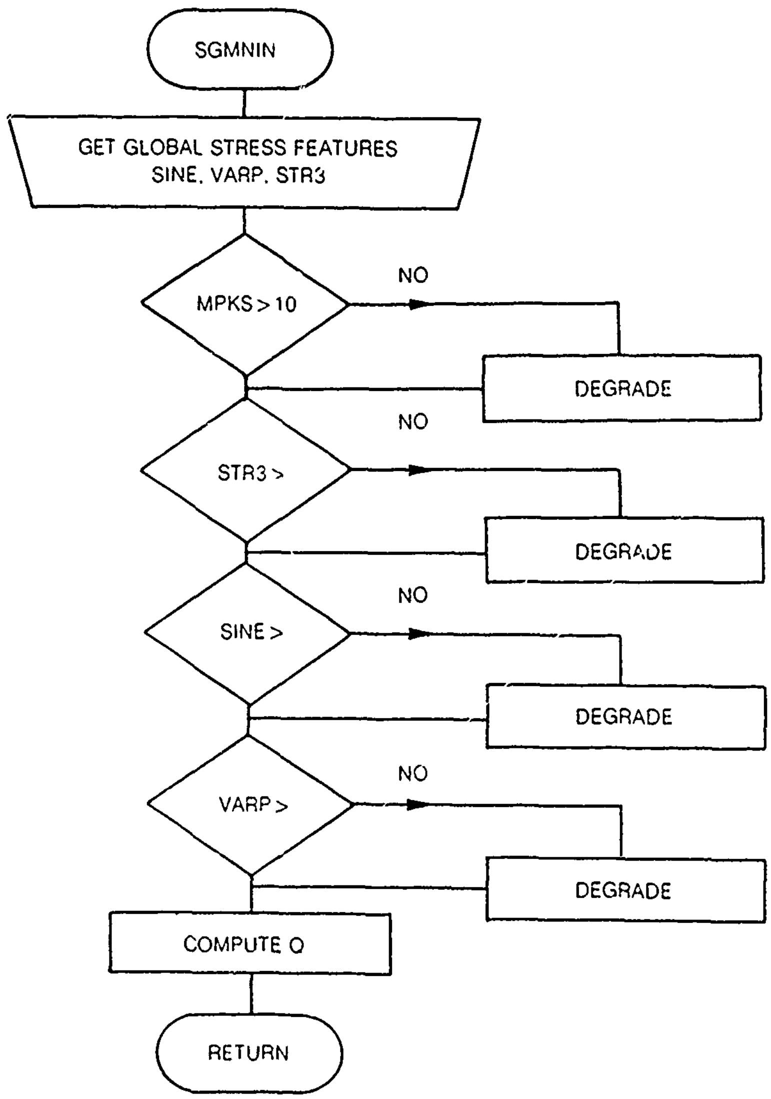


Figure 44. Flow Diagram for Subroutine SGMNLN

84-5-16-32

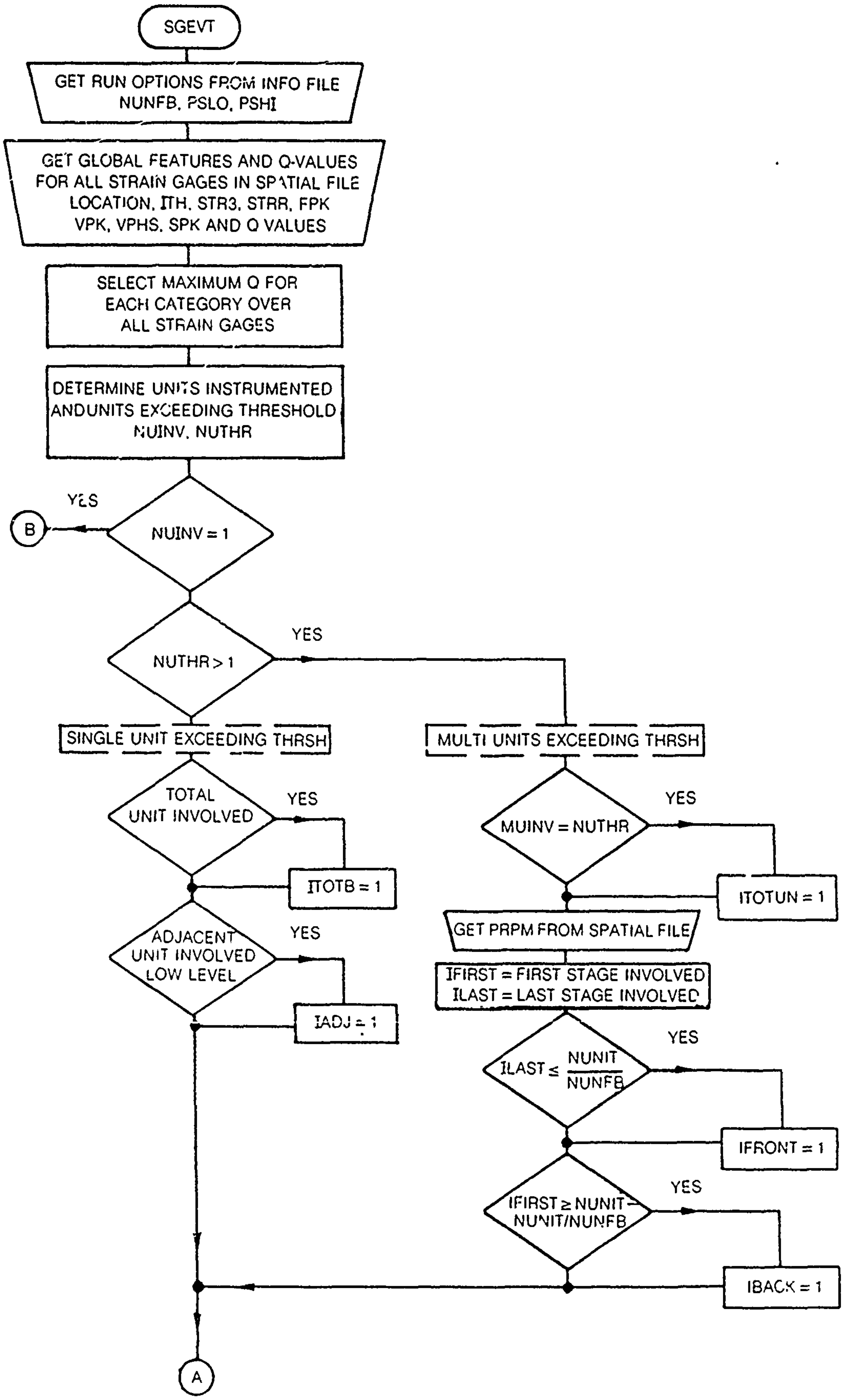


Figure 45. Flow Diagram for Subroutine SGEVT

84–5–16–35

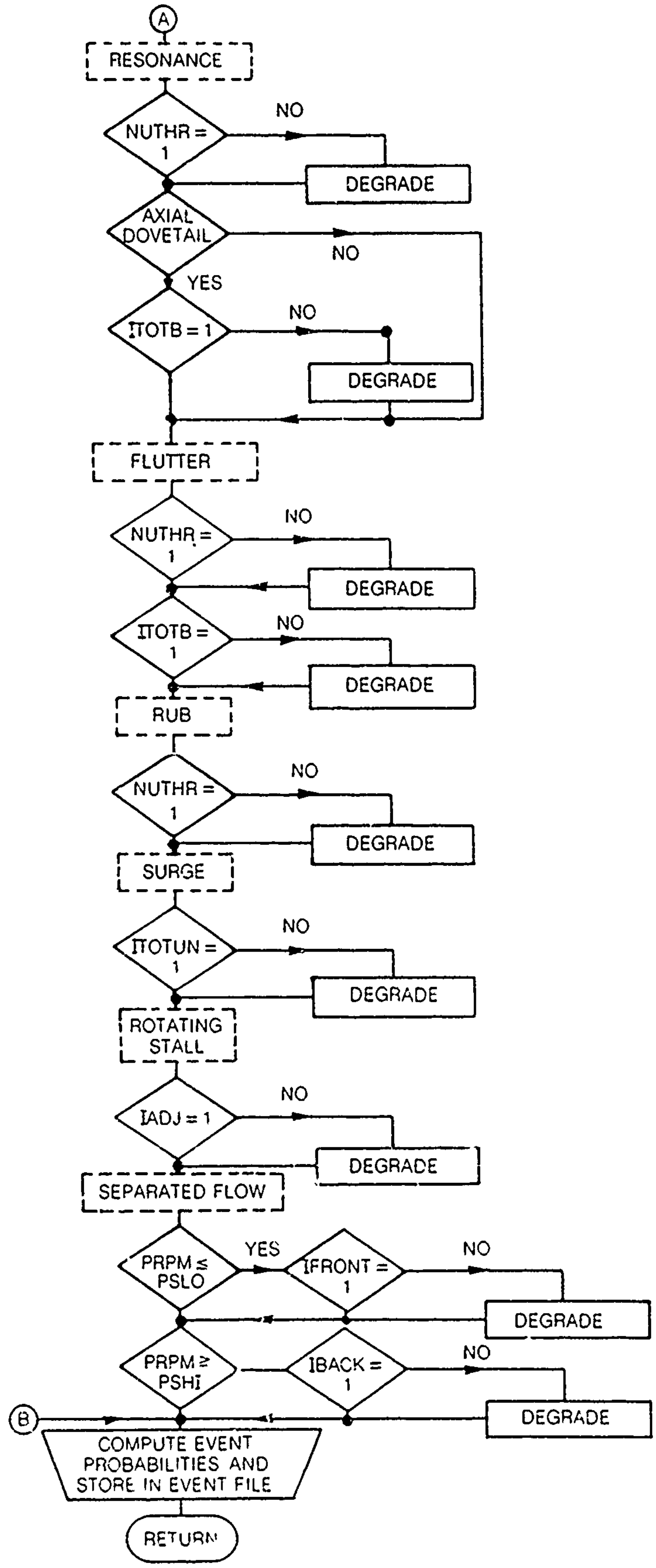


Figure 45a. Flow Diagram for Subroutine SGEVT (Cont'd)

84-5-16-36

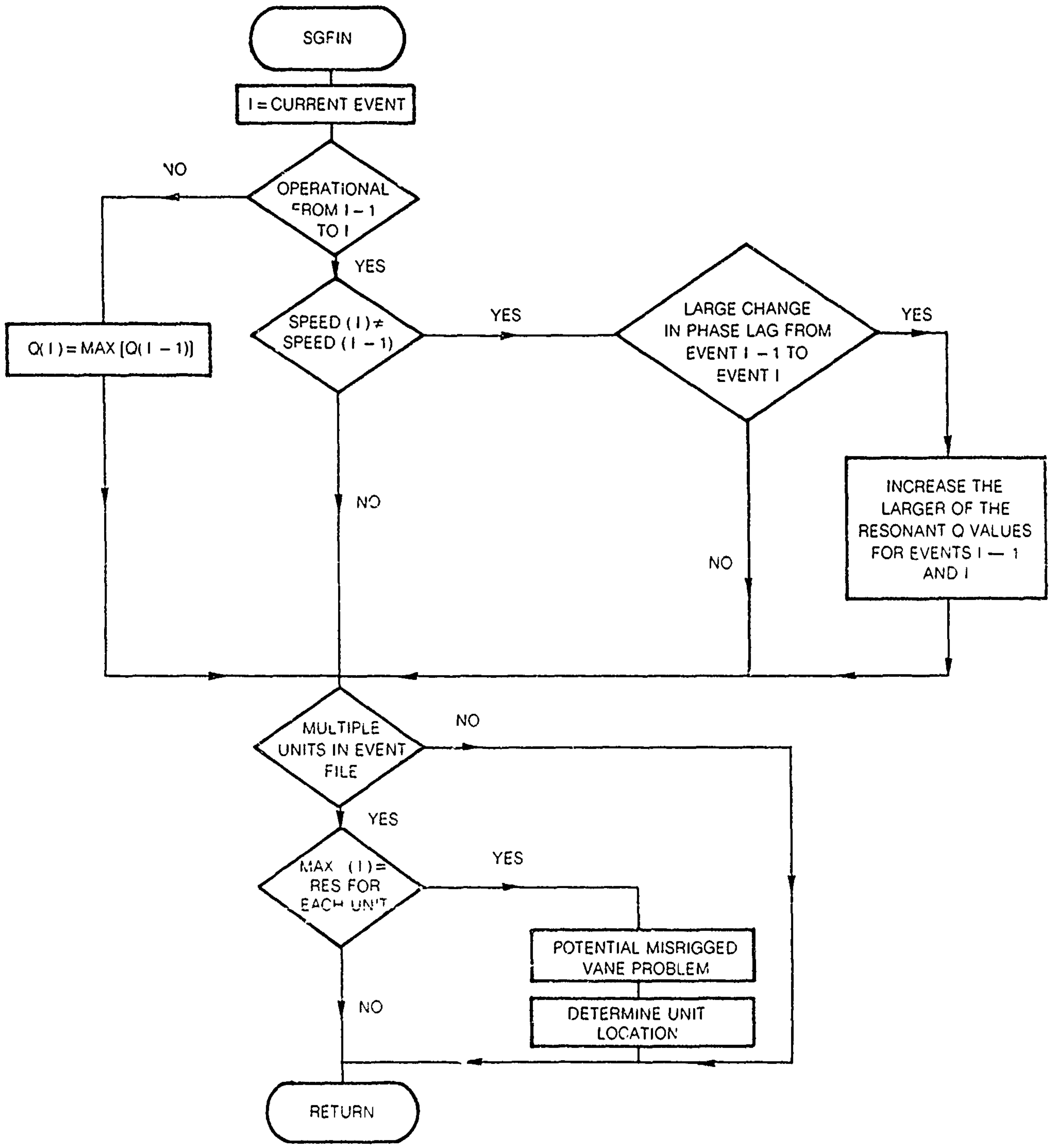


Figure 46. Flow Diagram for Subroutine SGFIN

85-3-55-3

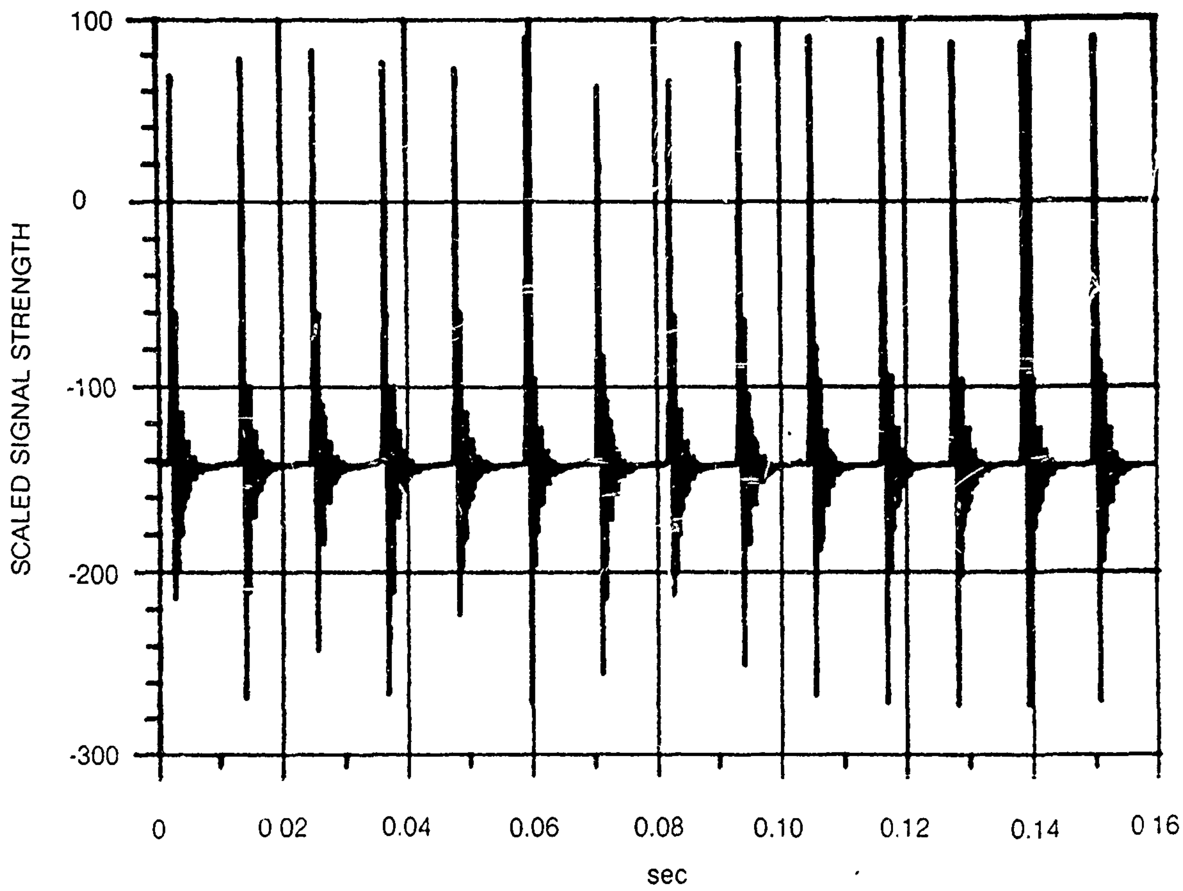


Figure 47. Typical Tachometer Signal

84-5-16-44

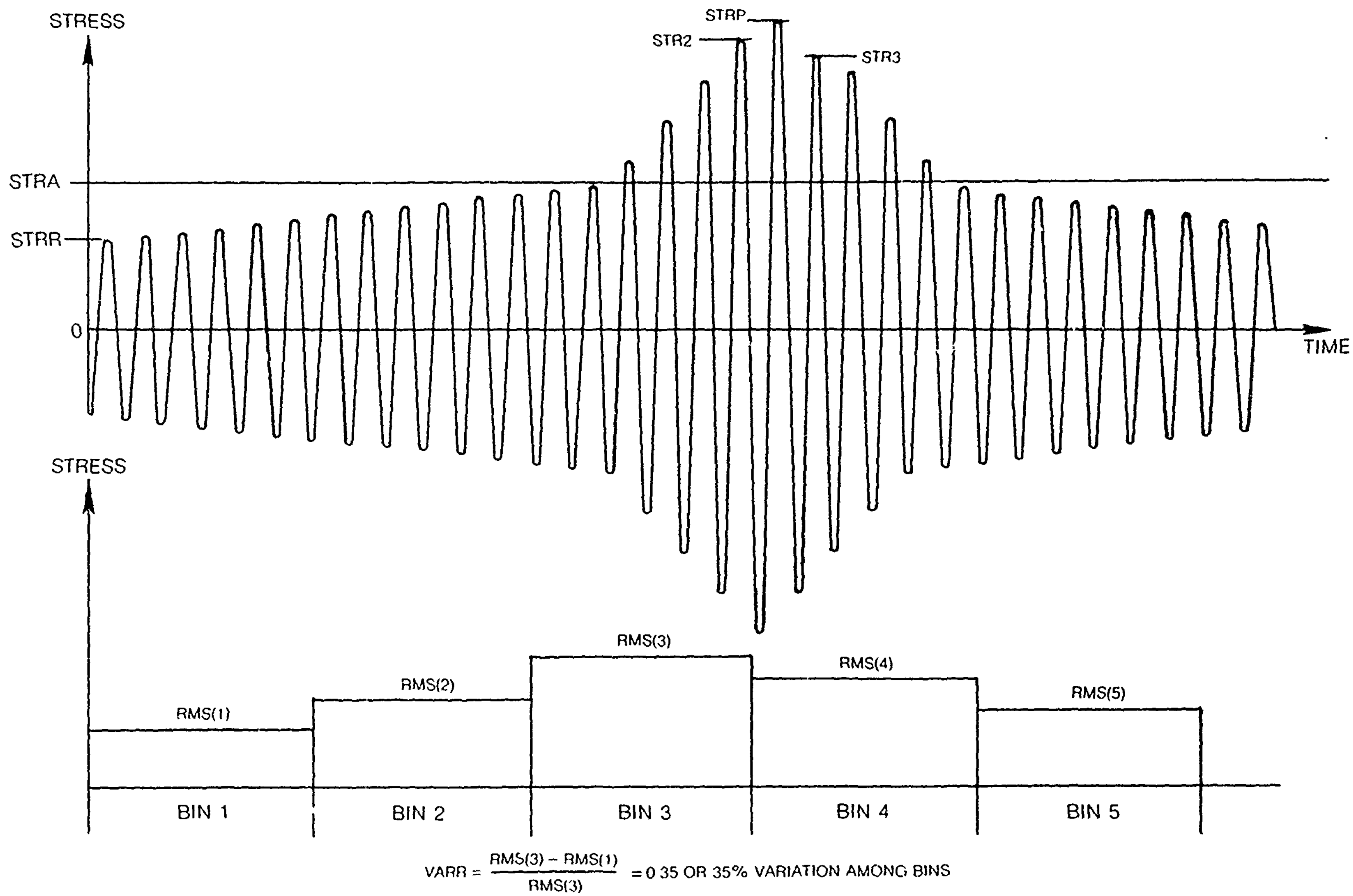


Figure 48. Stress Feature Example

84-5-16-38

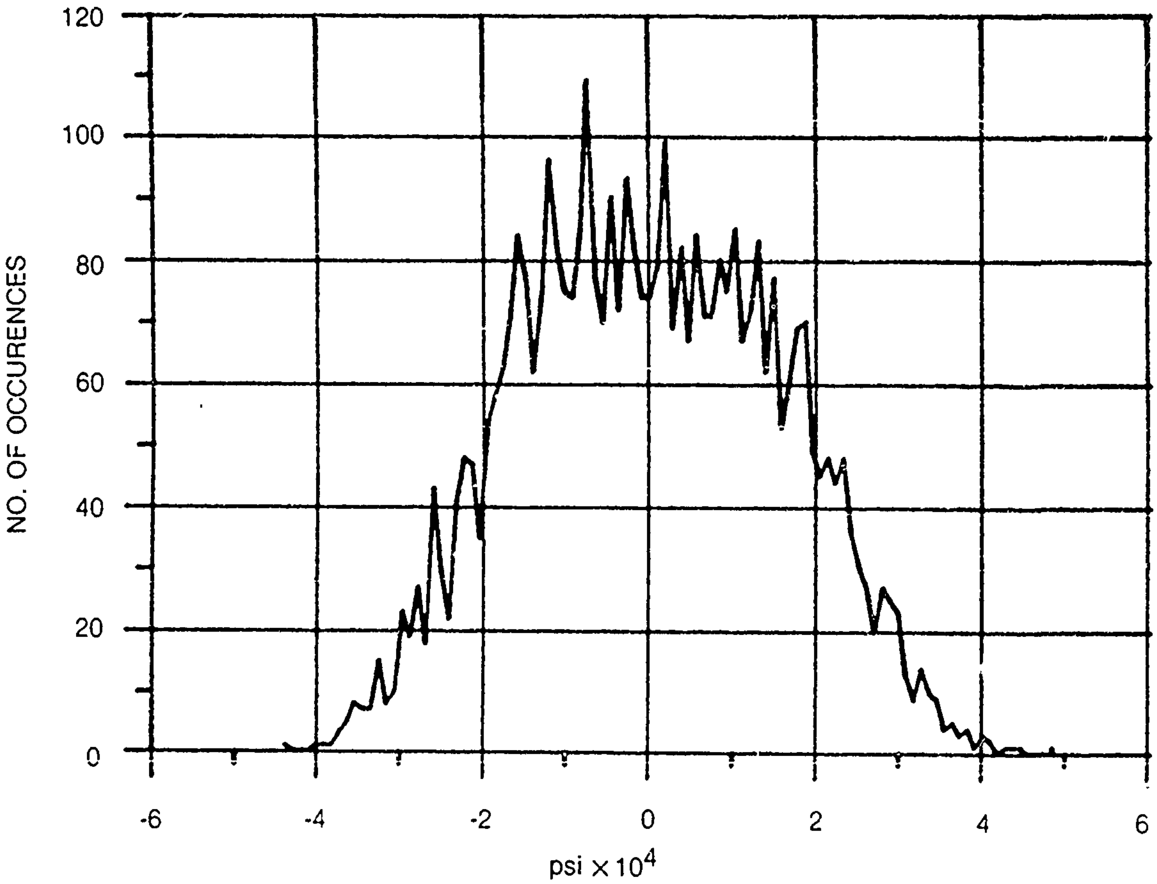


Figure 49. Typical Histogram for Flutter

84-5-16-39

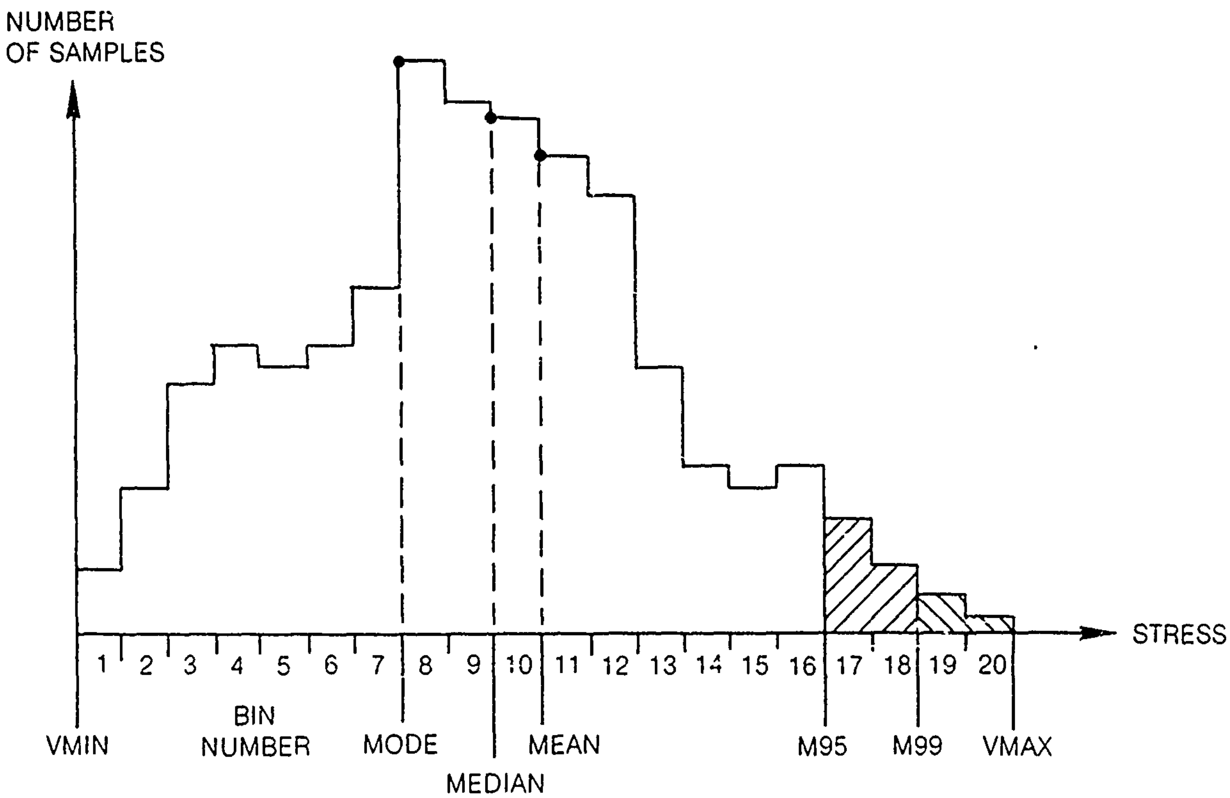


Figure 50. Illustration of Histogram Features

84-5-16-40

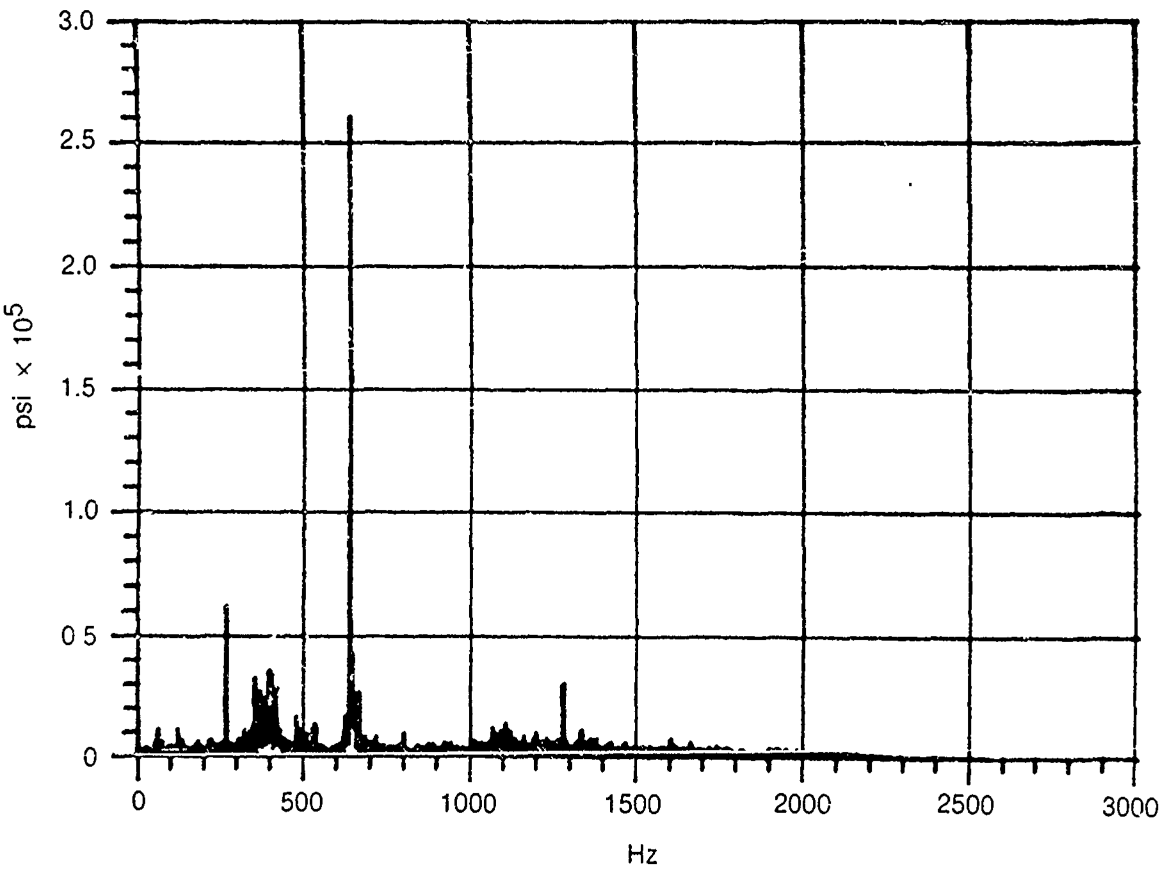


Figure 51. Typical FFT Magnitude Plot (Periodgram)

84-5-16-41

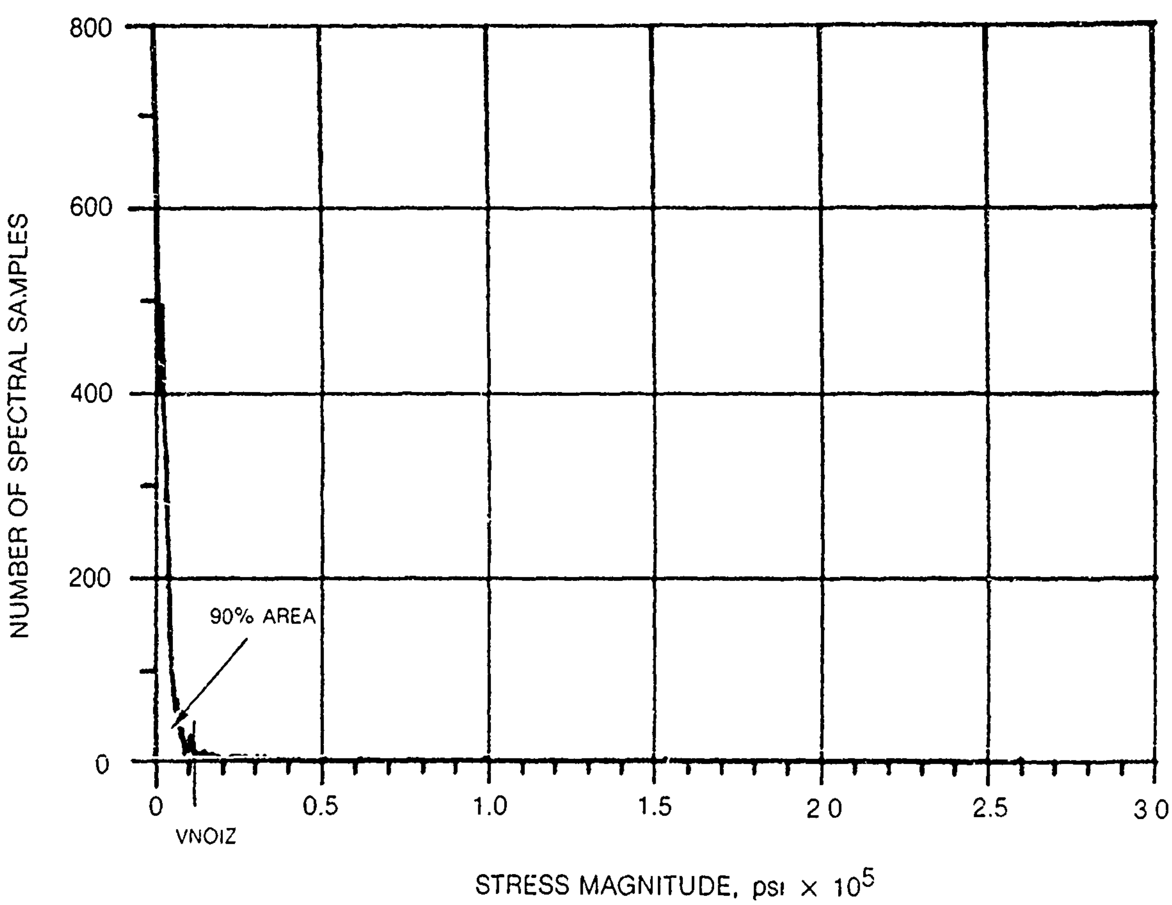


Figure 52. Typical Histogram of Power Spectrum

84-5-16-42

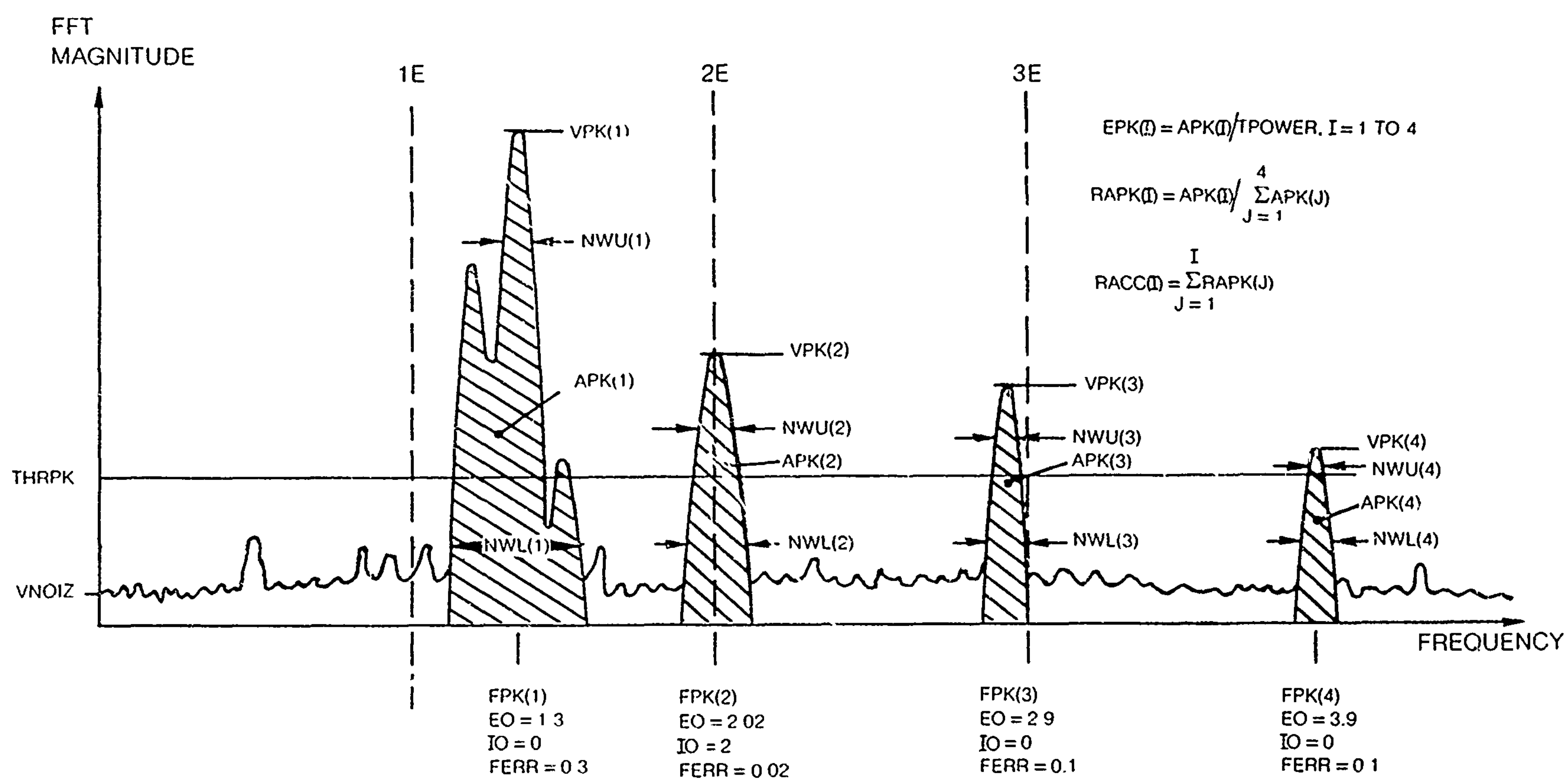


Figure 53. FFT Features Example

84-5-16-43

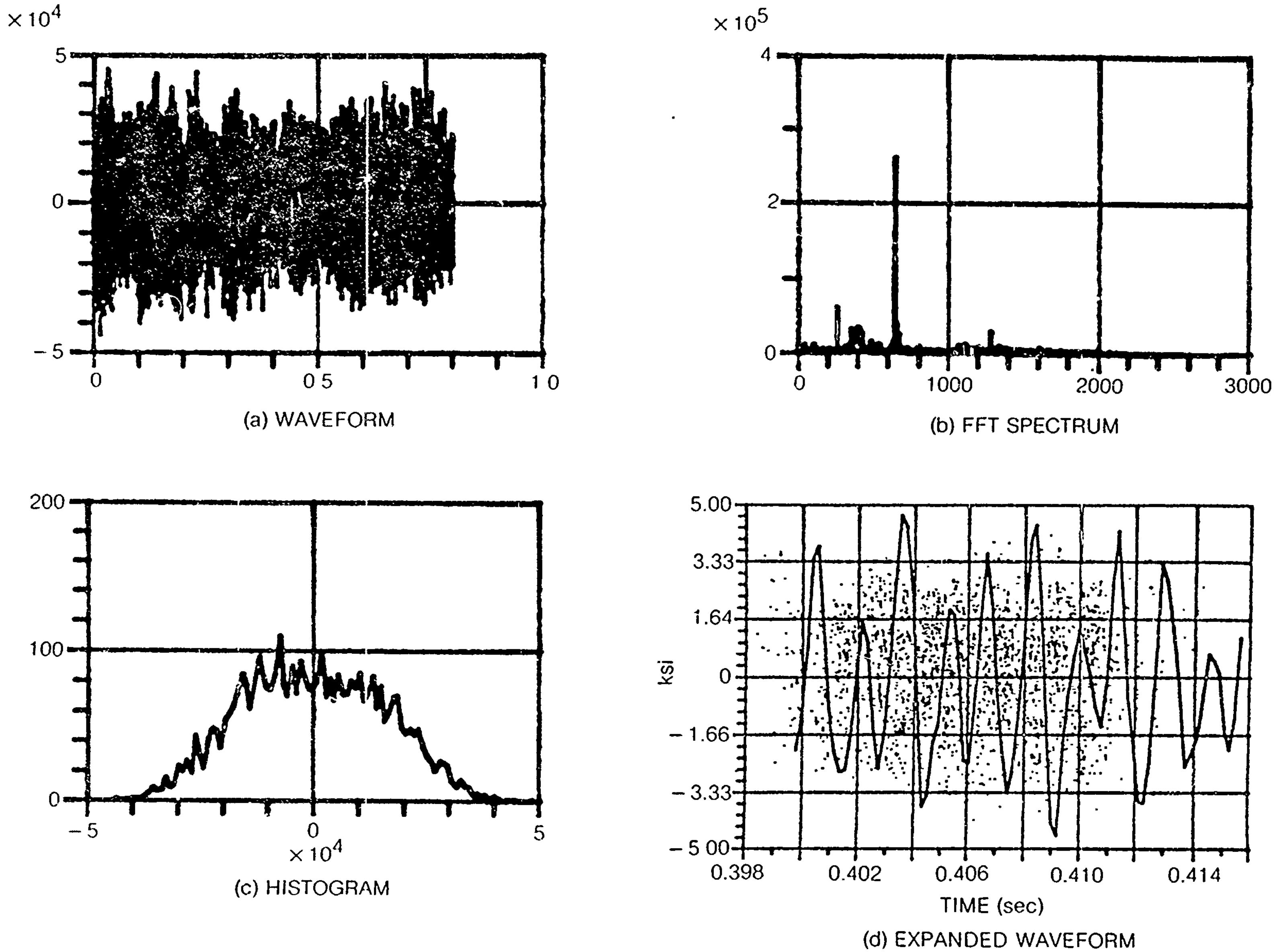


Figure 54. Strain-Gage Signal Characteristics (Flutter)

85-3-55-14

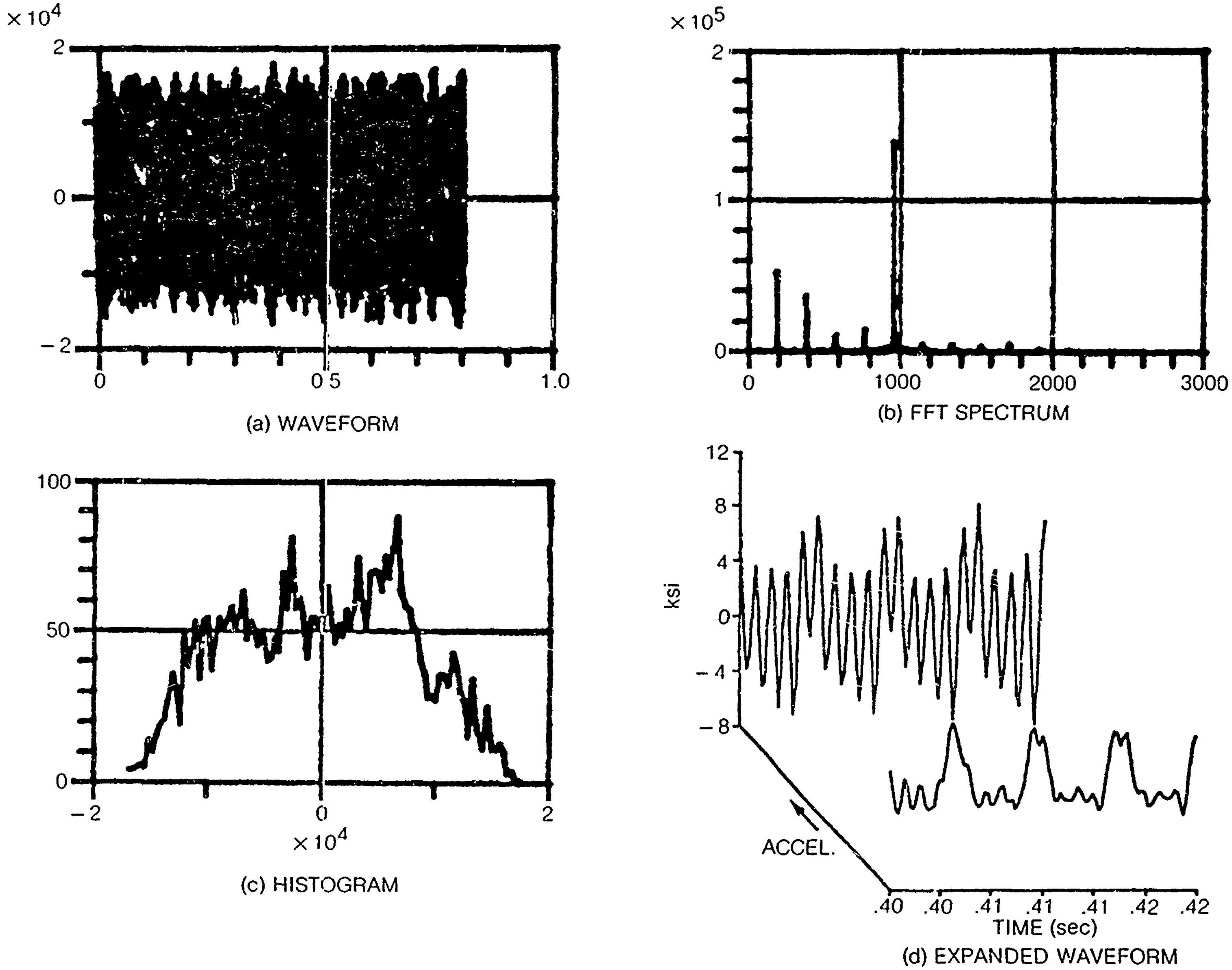


Figure 55. Strain-Gage Signal Characteristics (Resonance)

85-3-55-13

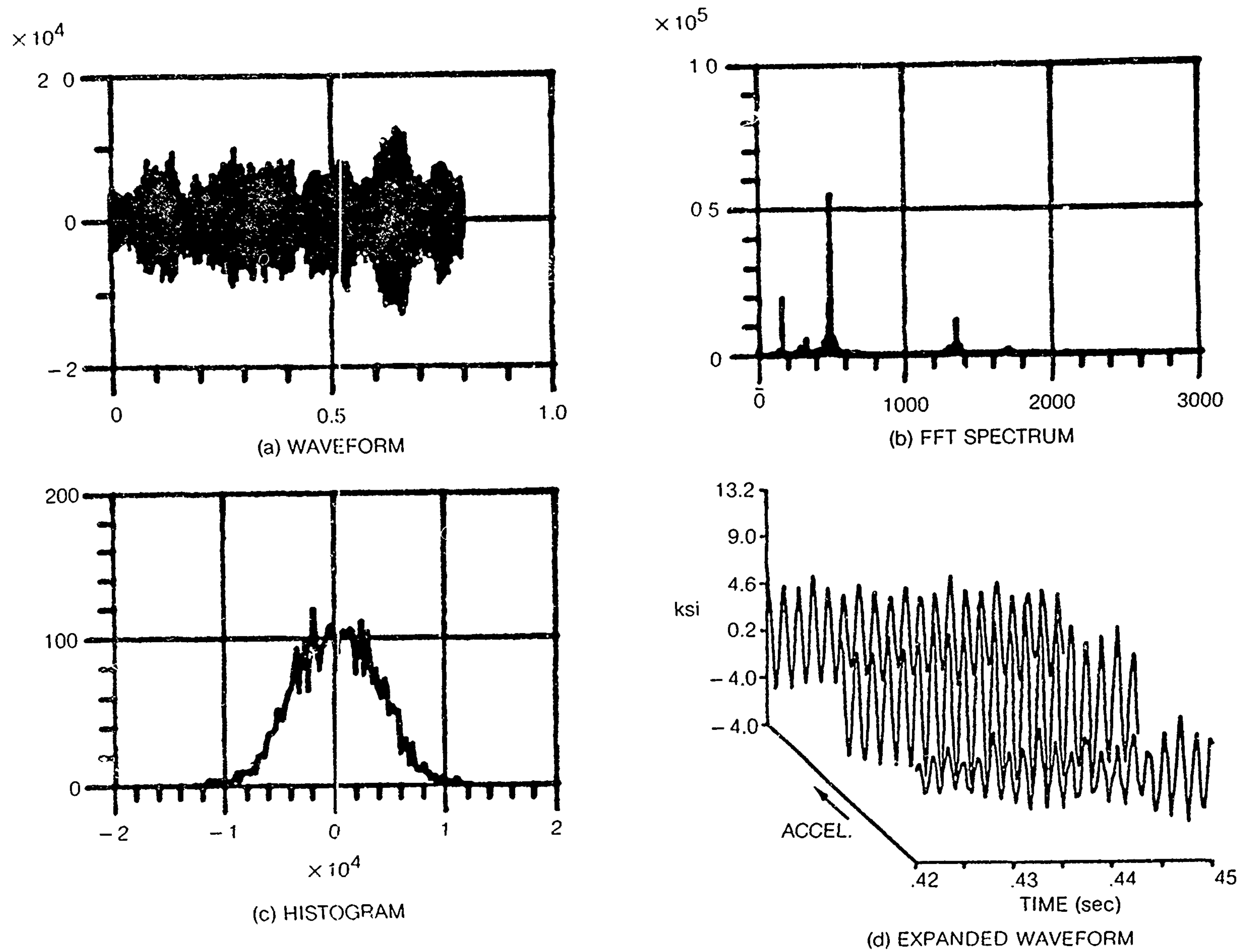


Figure 56. Strain-Gage Signal Characteristics (Separated Flow Vibration)

85-3-55-8

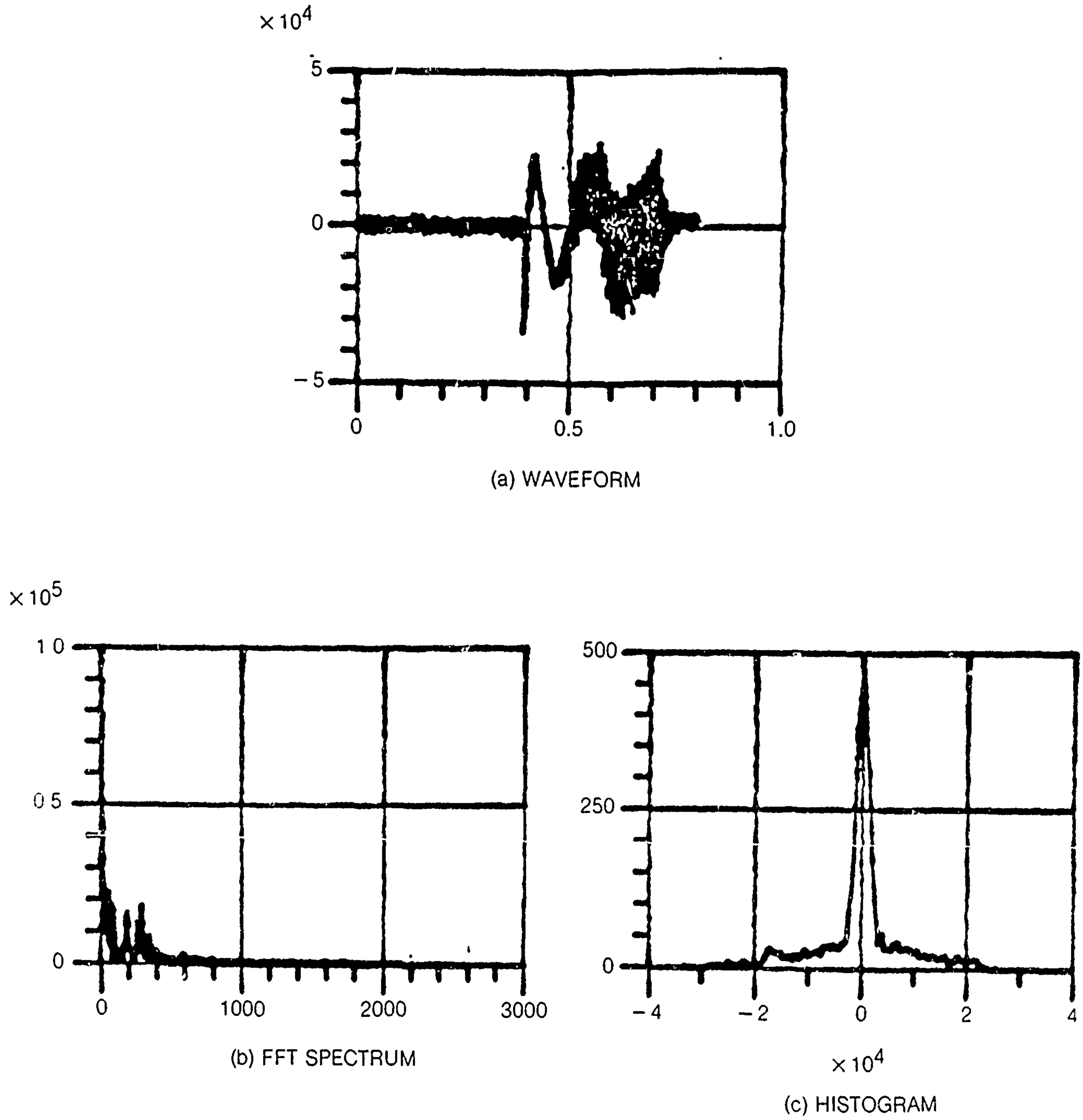


Figure 57. Strain-Gage Signal Characteristics (Surge/Rotating Stall)

85-3-65-9

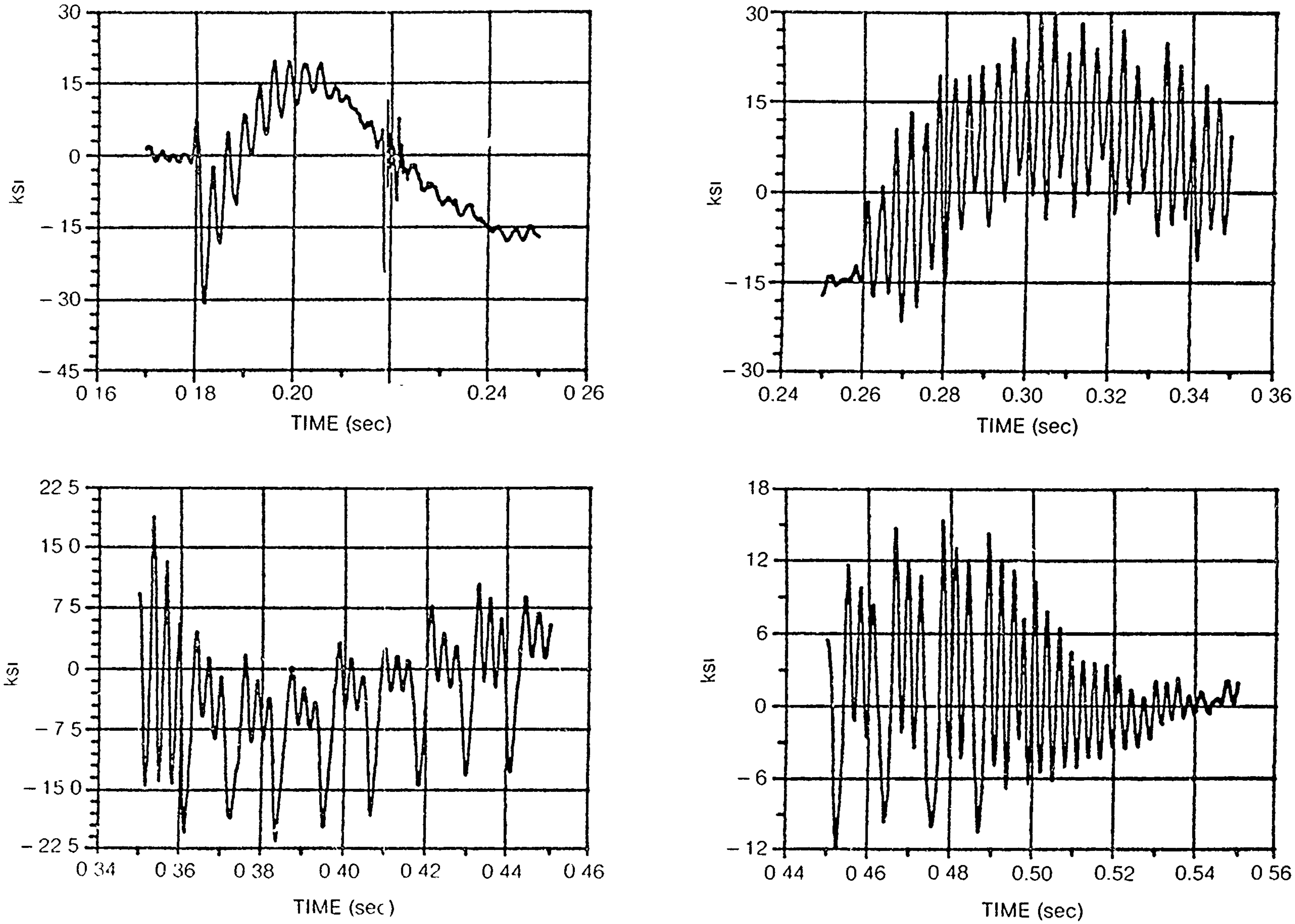


Figure 58. Expanded Surge/Rotating Stall Waveforms

85-3-55-10

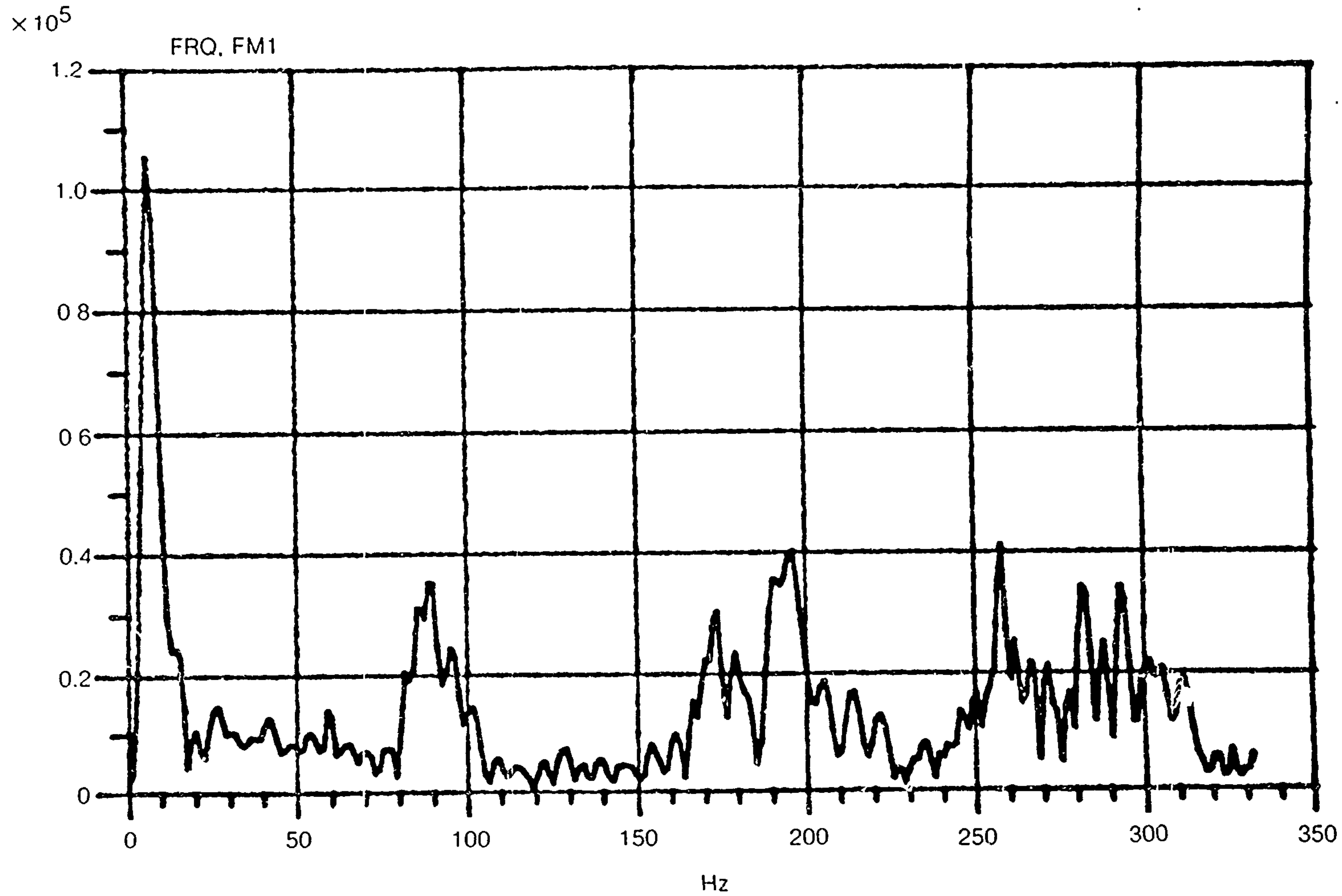


Figure 59. Expanded FFT Spectrum for Surge and Rotating Stall

85-3-55-11

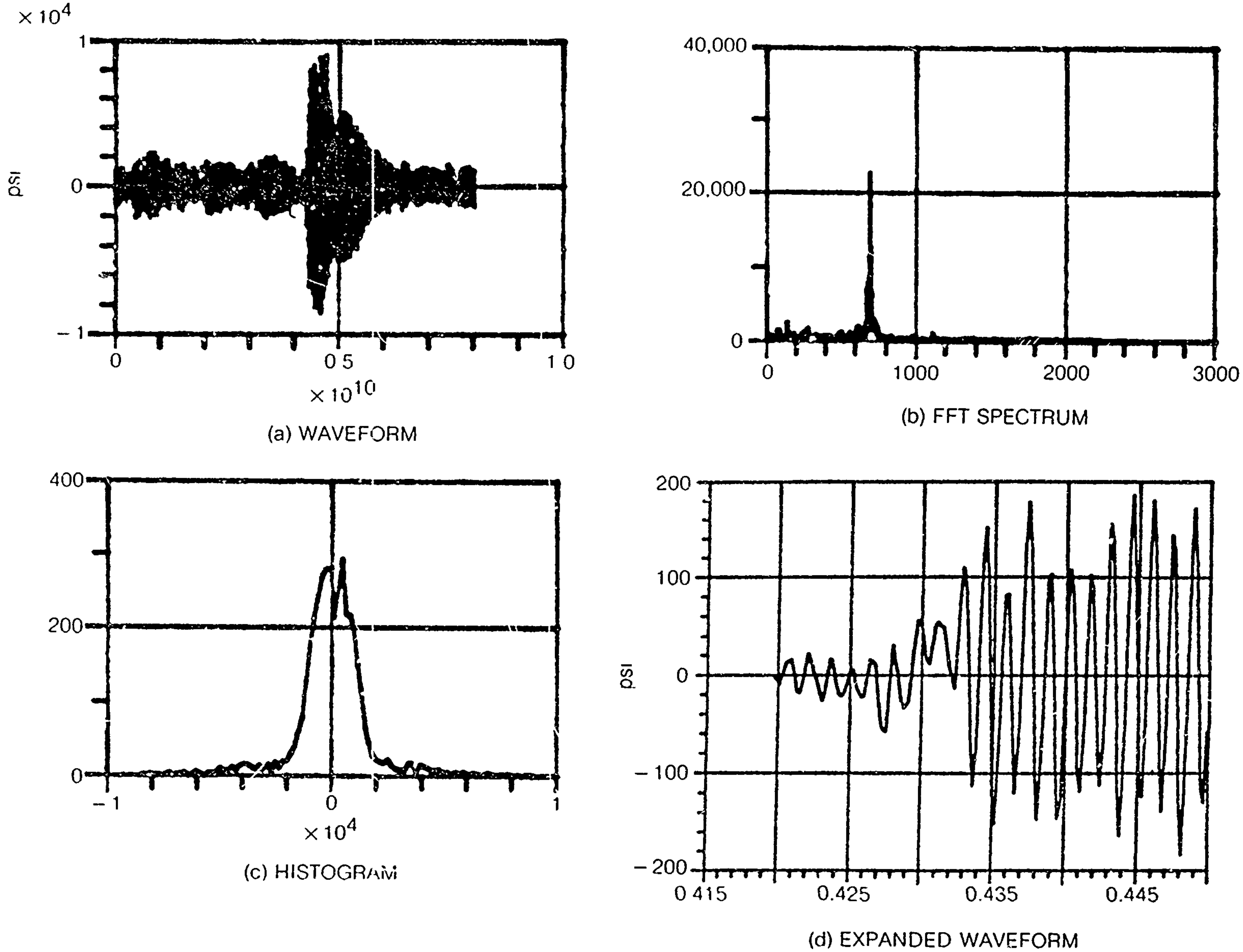


Figure 60. Strain-Gage Signal Characteristics (Surge)

85-3-55-12

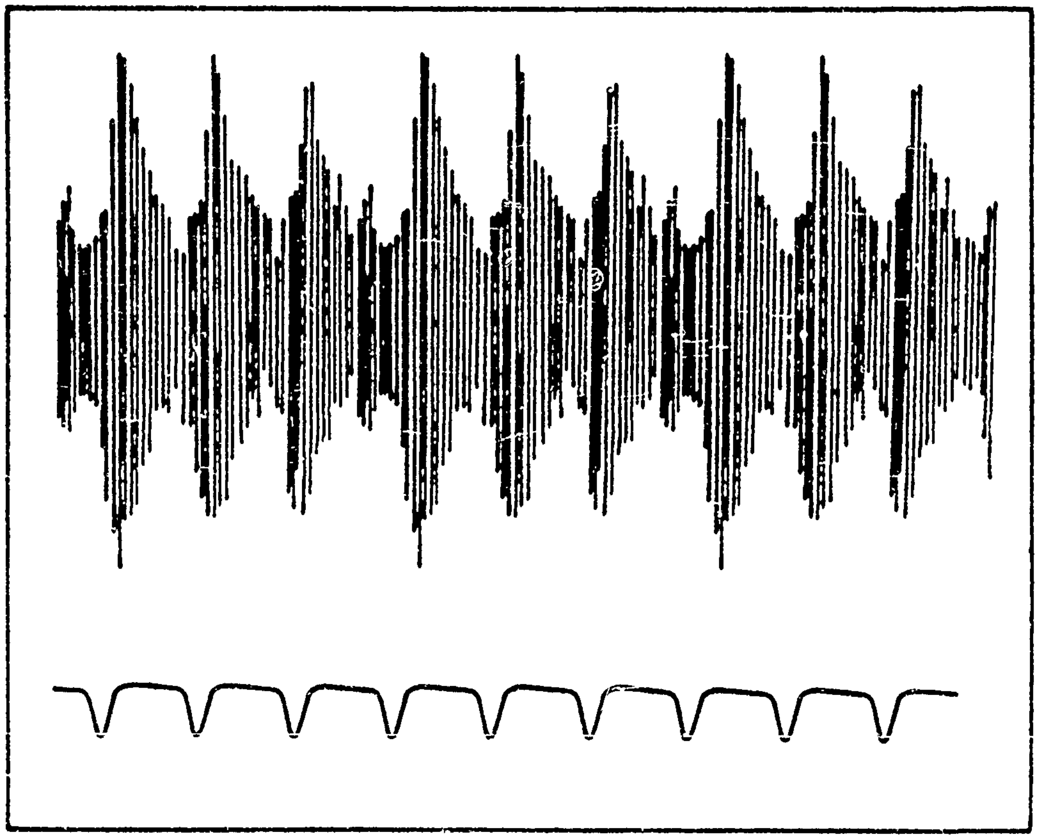


Figure 61. Typical Tip-Rub Waveform

85-3-55-6

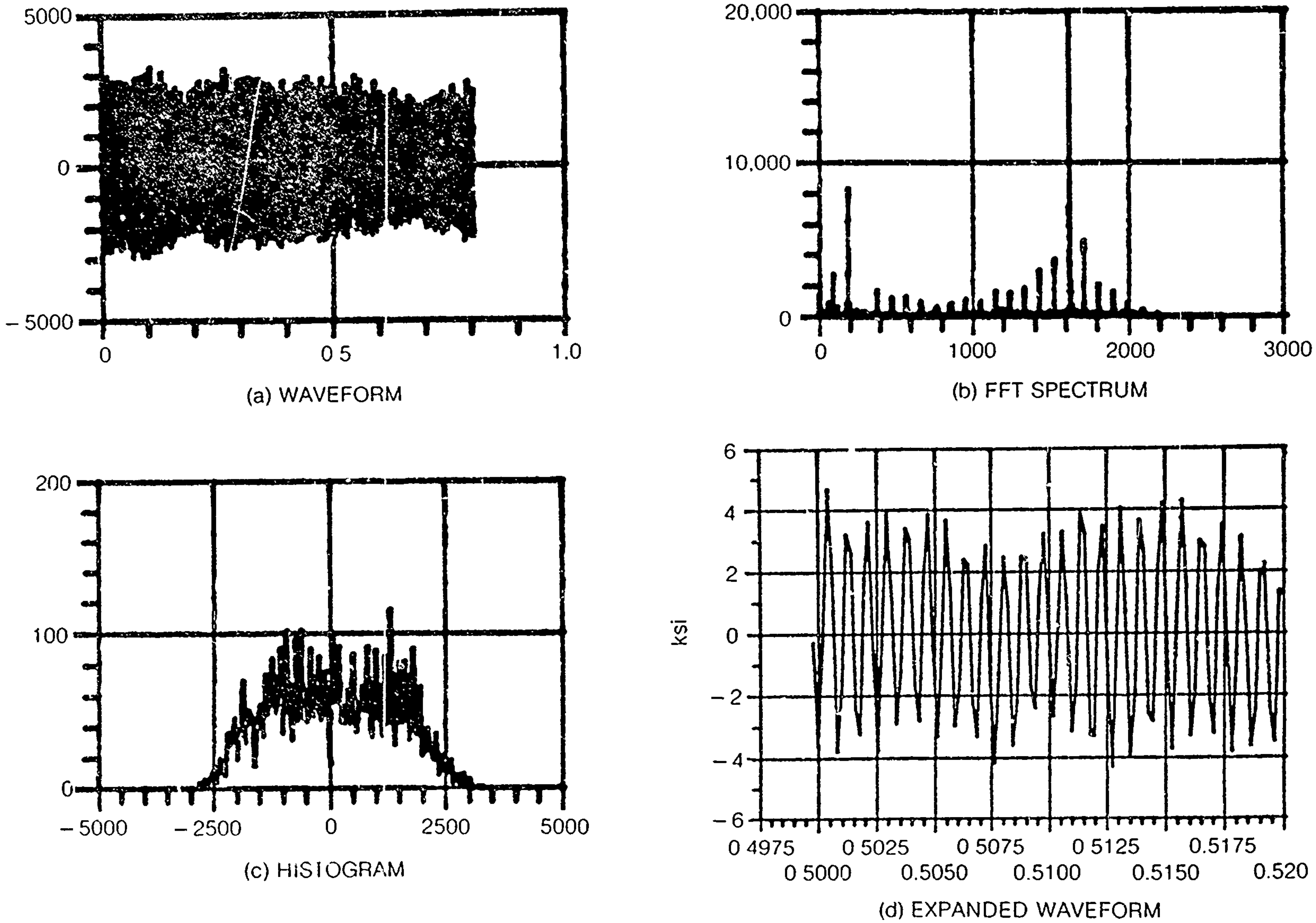


Figure 62. Strain-Gage Signal Characteristics (Misrigged Vane)

85-3-55-7

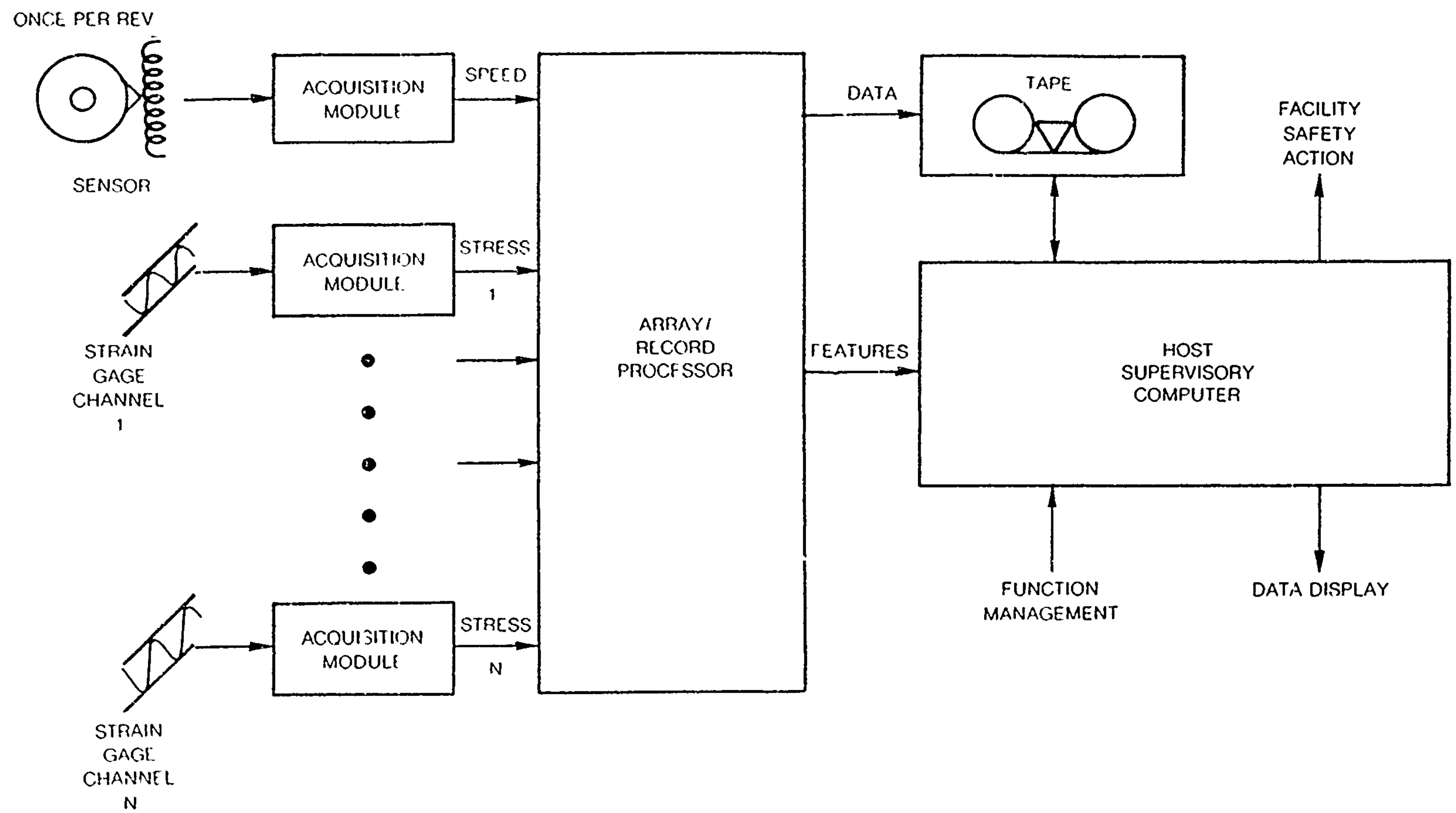


Figure 63. On-Line Hardware System

84-11-8-1

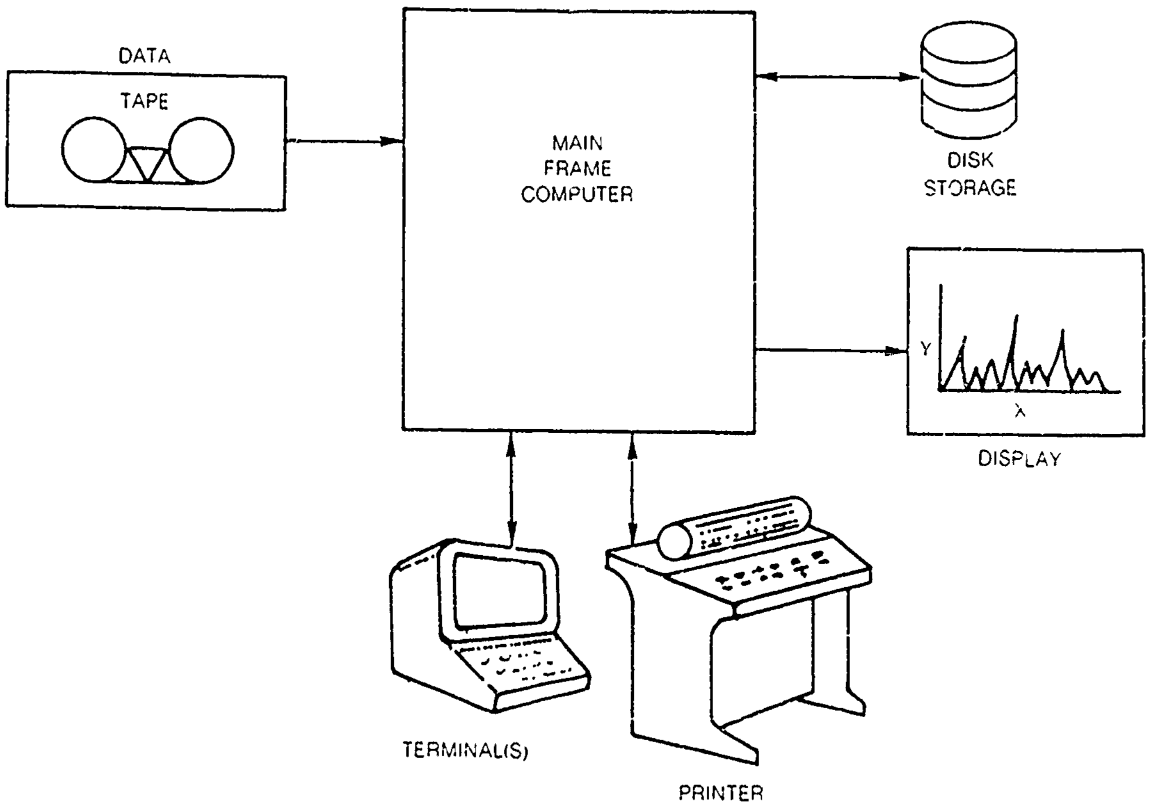


Figure 64. Off-line Hardware System

84-11-8-2

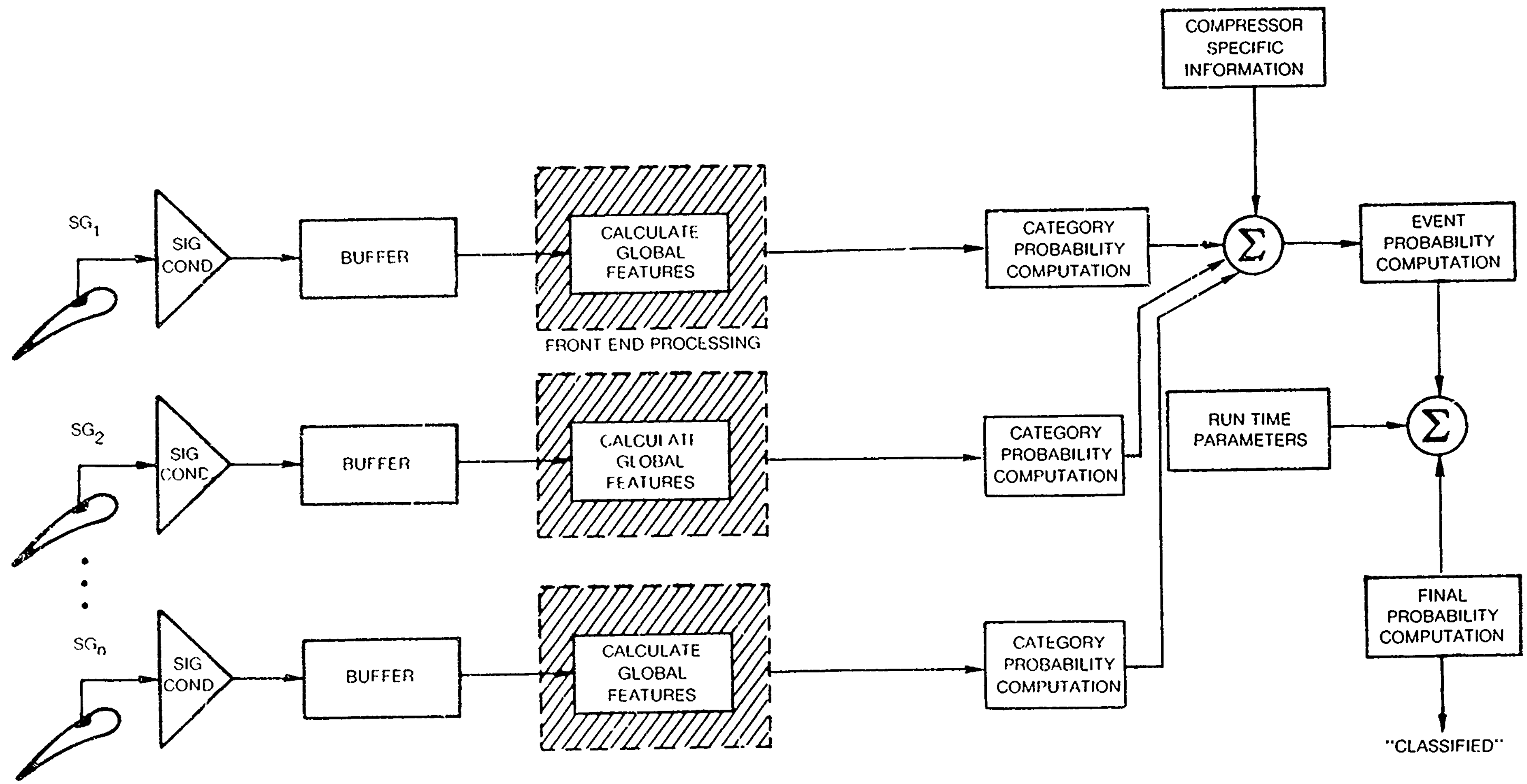


Figure 65. Overall Software Flow Diagram

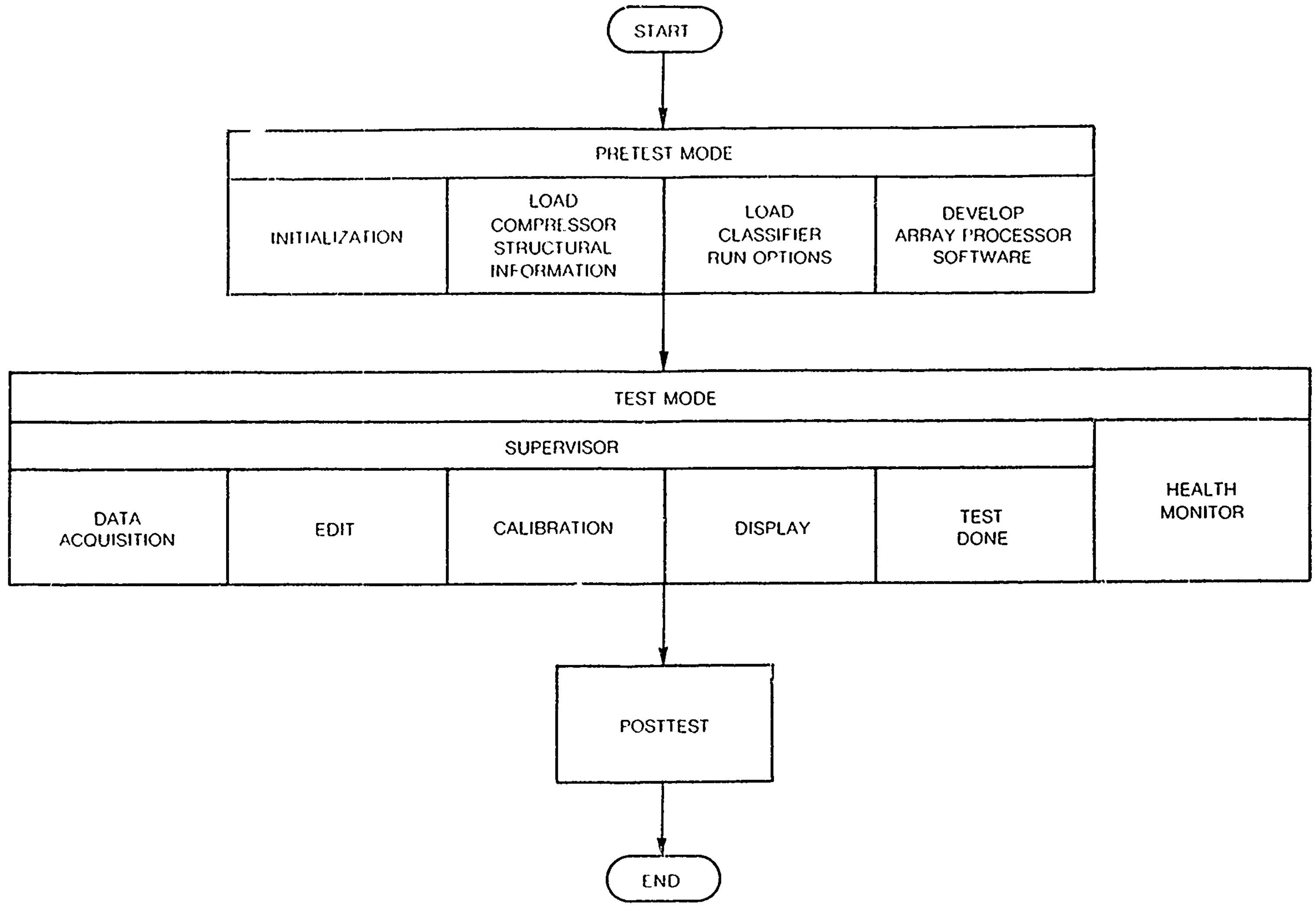


Figure 66. Host On-line Operational Modes

84-11-8-4

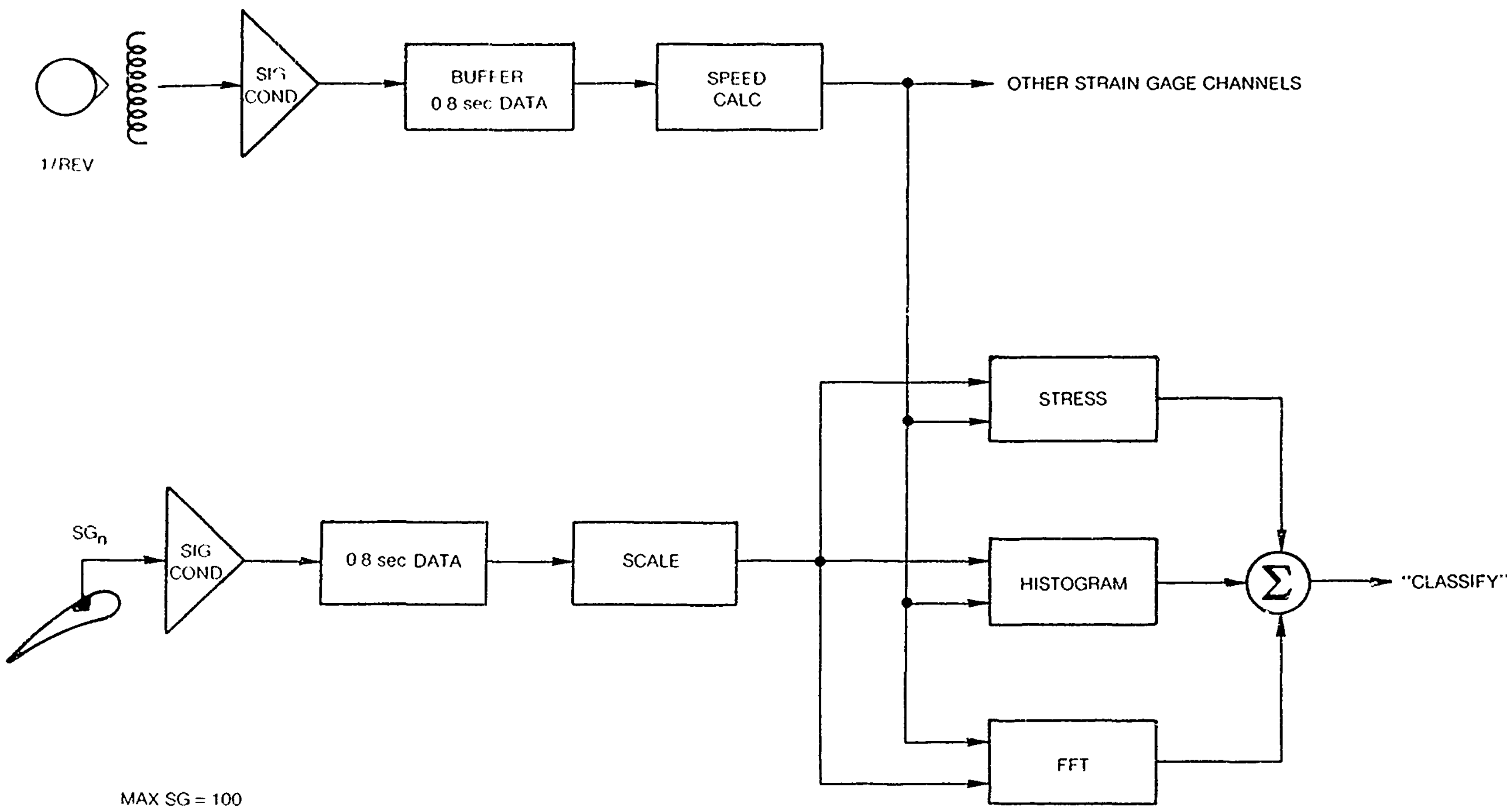


Figure 67. Front End Processing

84–11–8–5

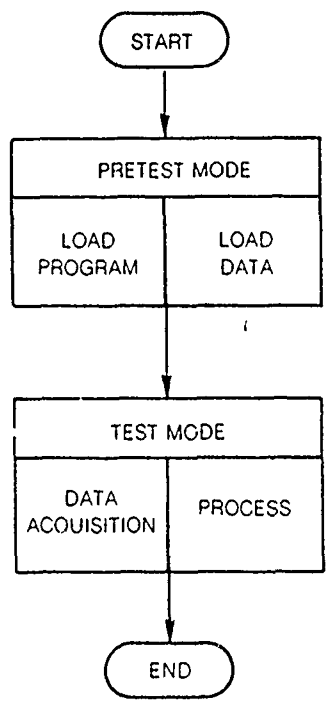


Figure 68. Array Processor Operational Modes

84-11-8-6

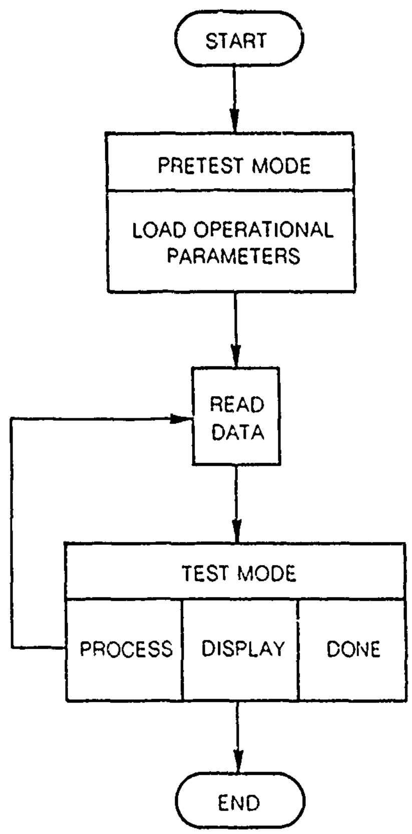


Figure 69. Host Off-line Operational Modes

84-11-8-7

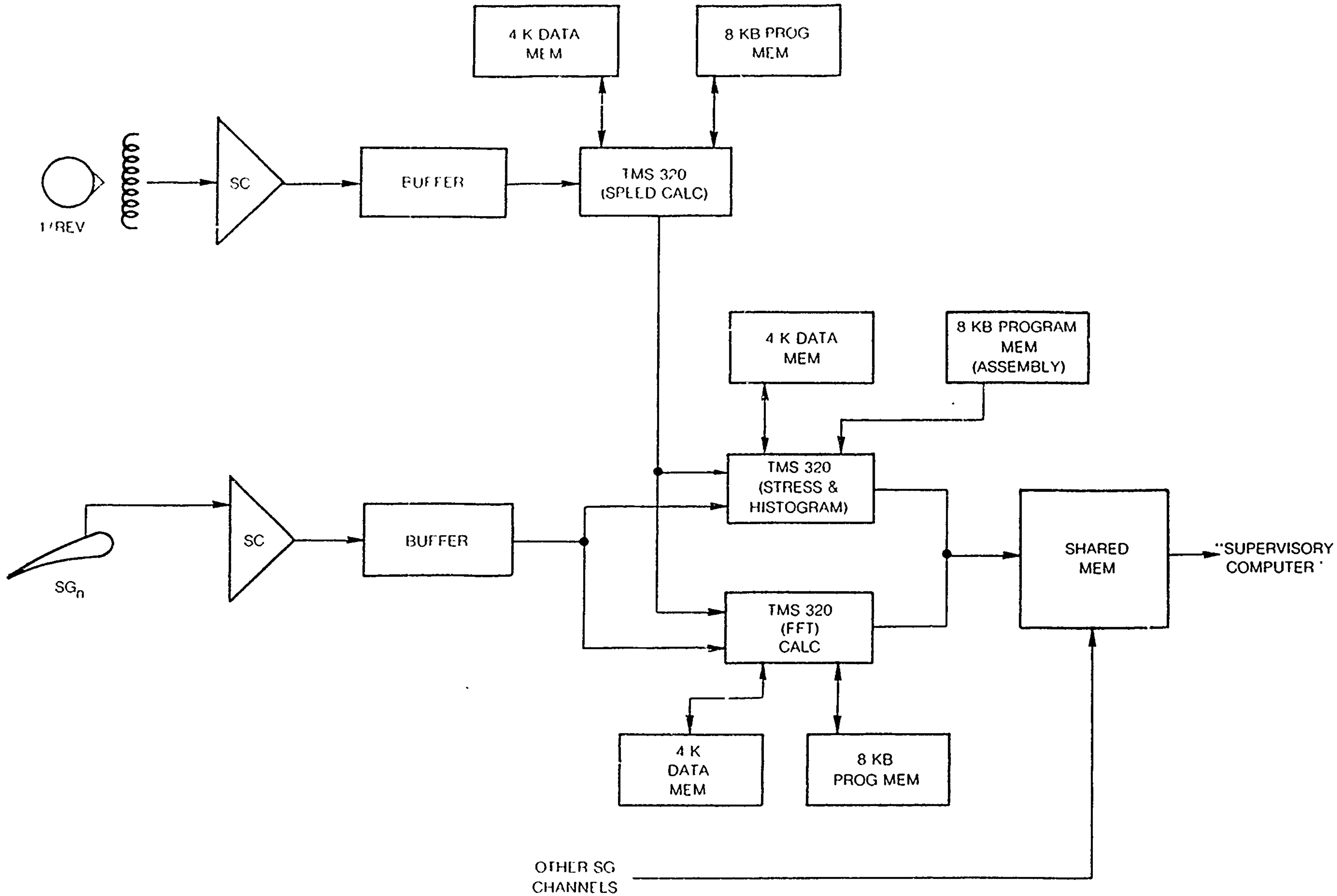


Figure 70. Hardware Option I

84-11-8-8

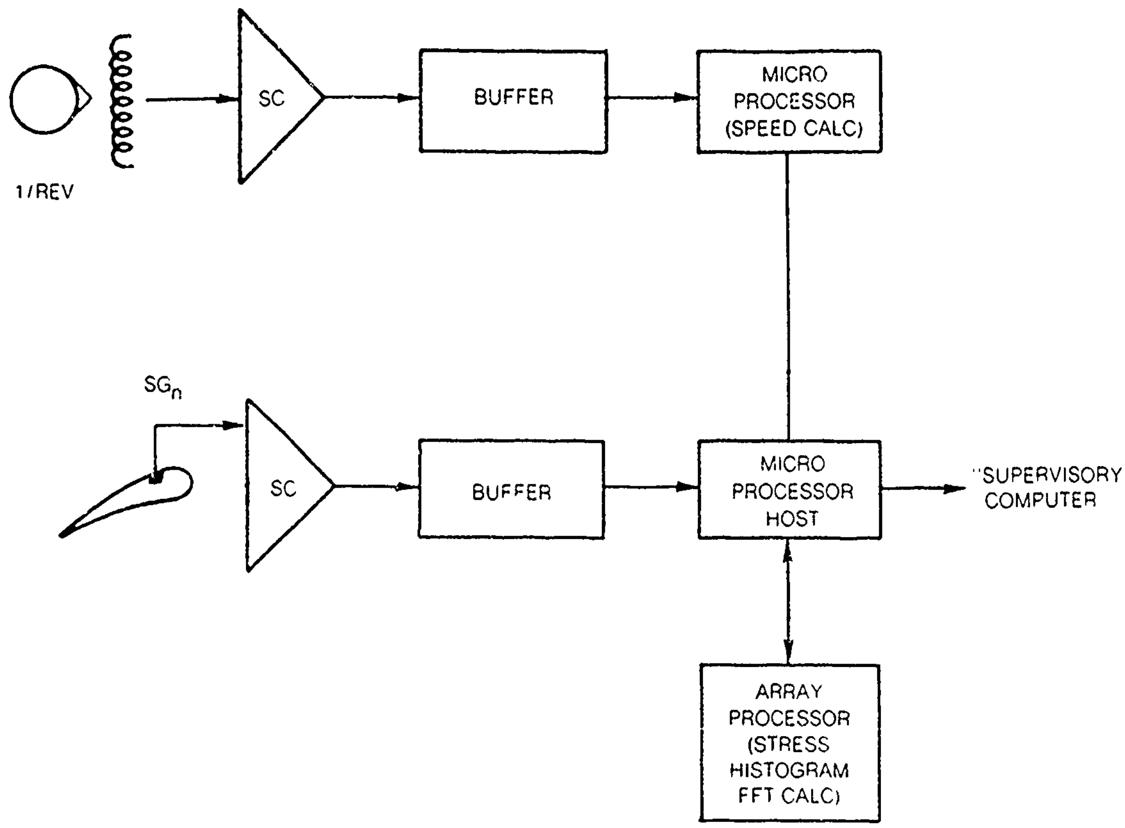


Figure 71. Hardware Option II

84-11-8-9

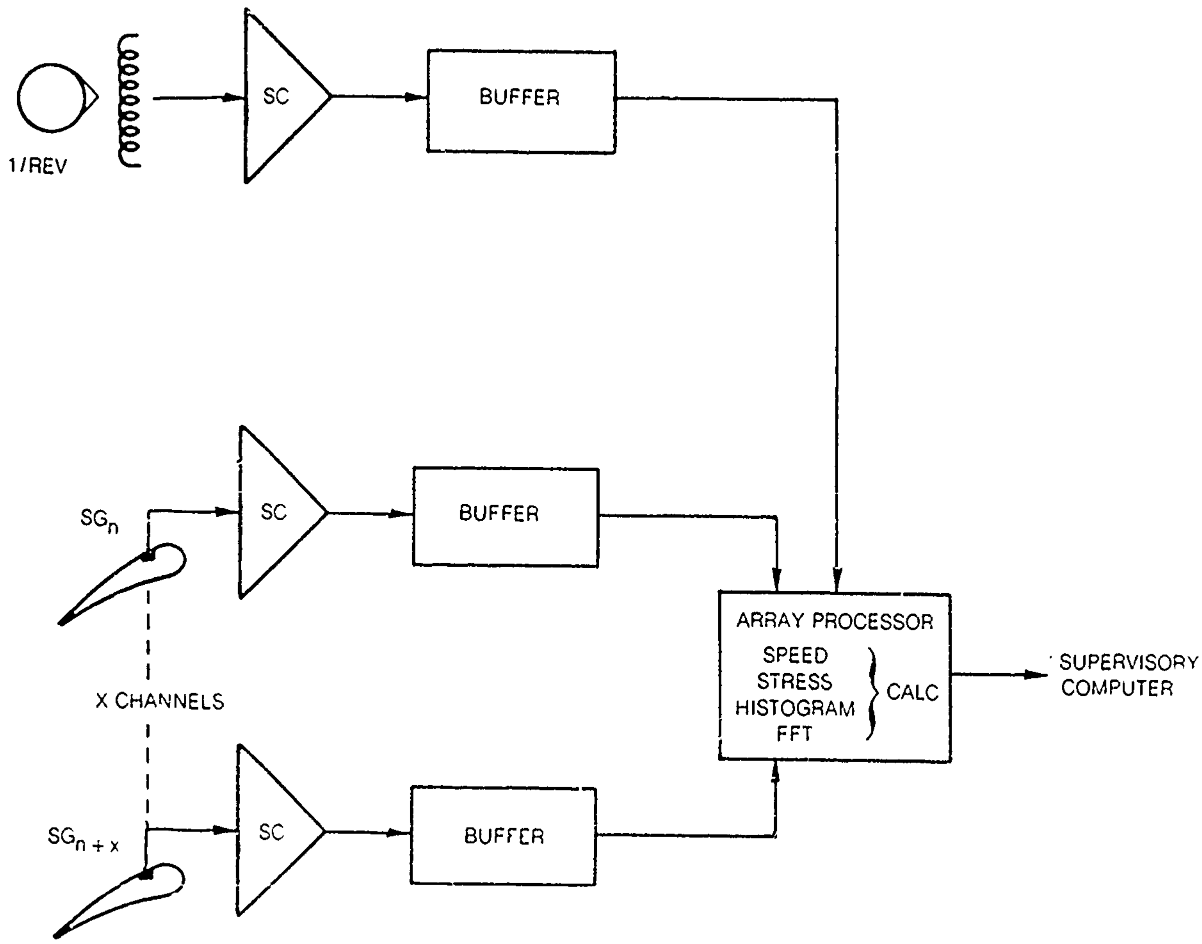


Figure 72. Hardware Option III

84-11-8-10

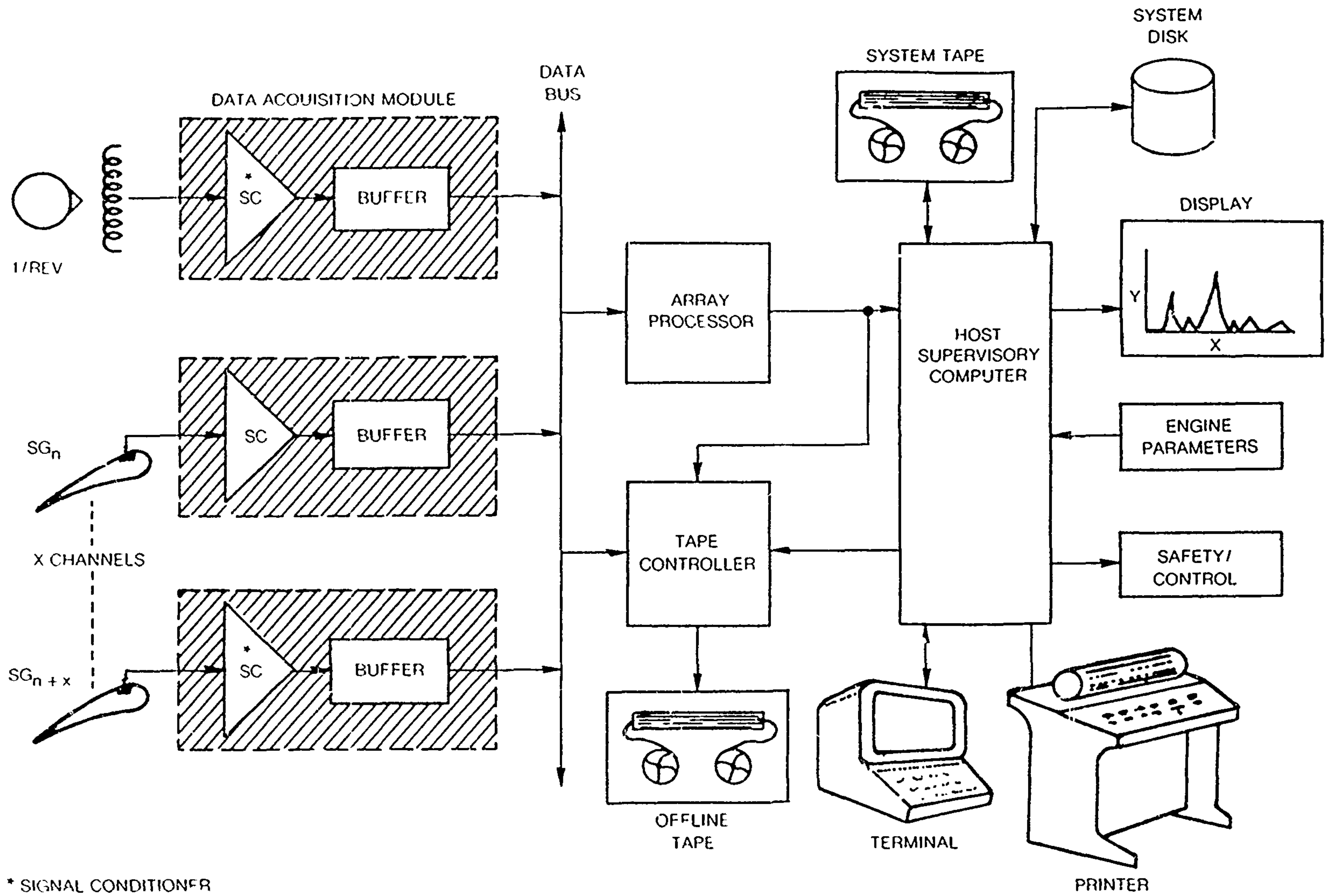


Figure 73. Overall Hardware Block Diagram

84-11-8-11

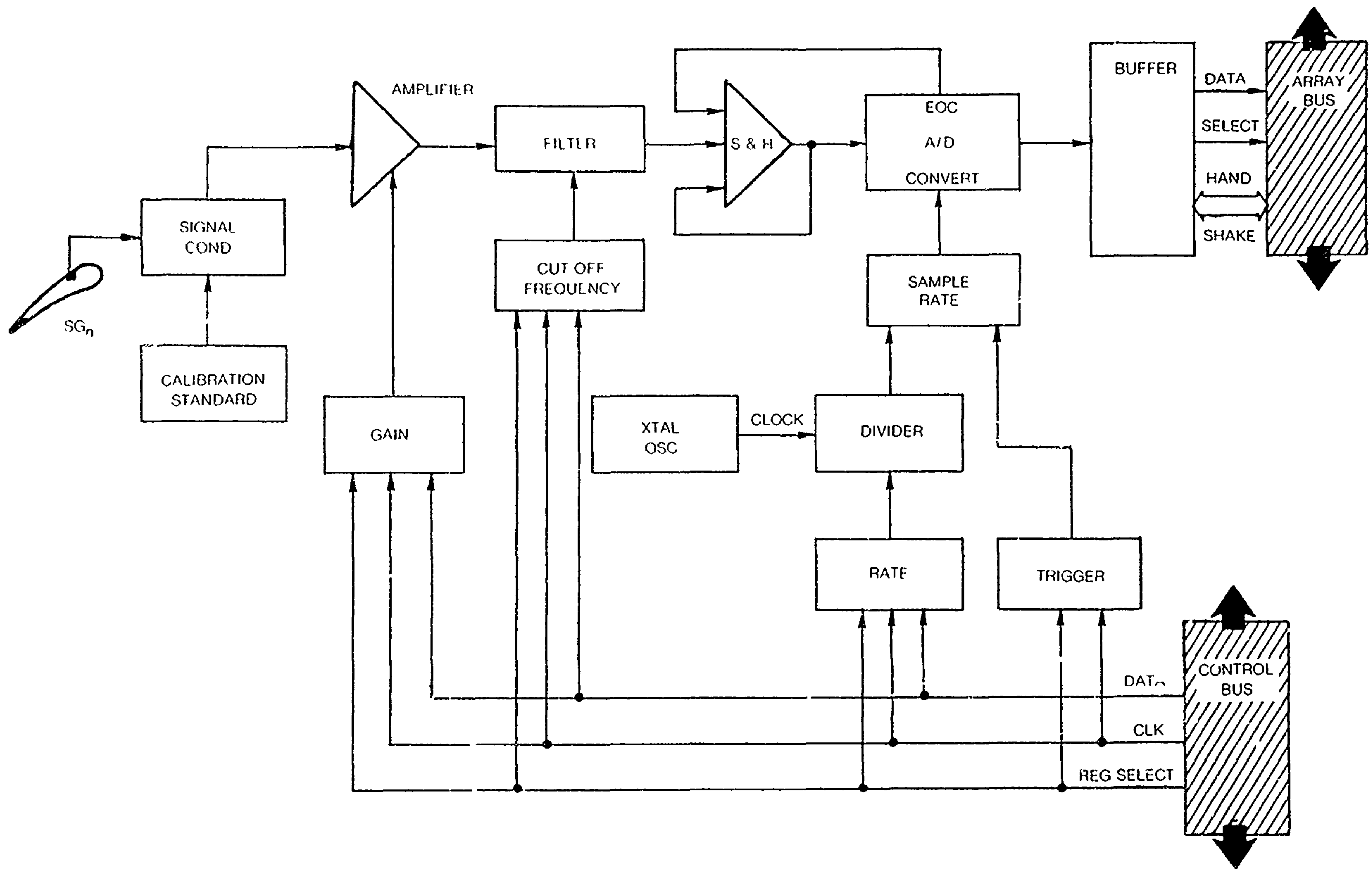


Figure 74. Data Acquisition Module

84-11-8-12

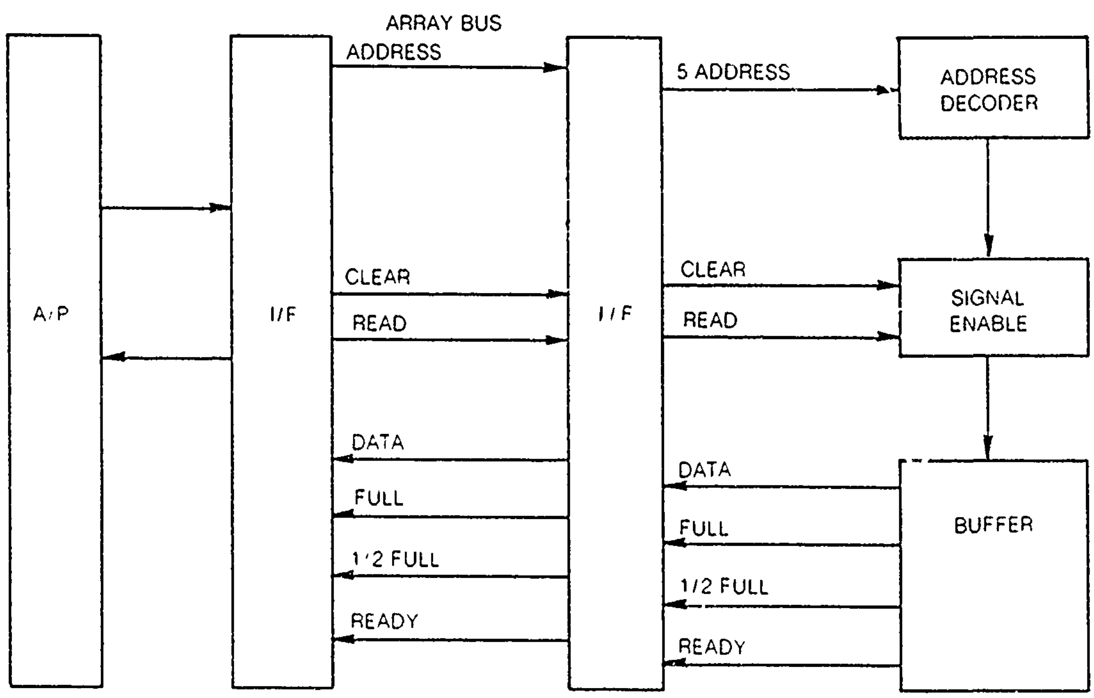


Figure 75. Array Interface

84-11-8-13

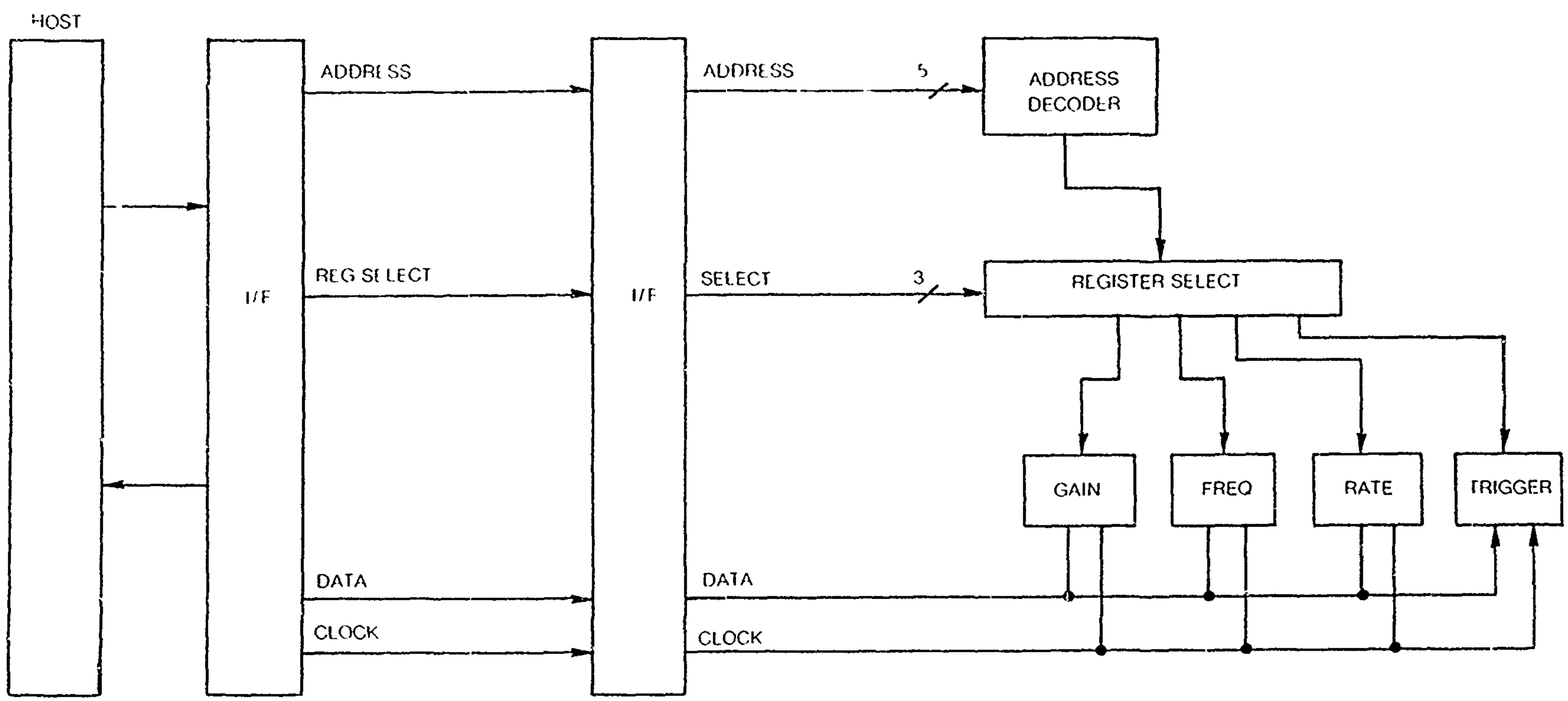


Figure 76. Control Interface

84-11-8-14

U.S.Government Printing Office 1986 - 646-067/40699